Calibration method for high frequency microphones

S. Ollivier[a], E. Salze[a], M. Averiyanov[b], P. V. Yuldashev[a], V. Khokhlova[b] and P. Blanc-Benon[a]

[a]Laboratoire de Mecanique des Fluides et d'Acoustique, 36 Av Guy de Collongue 69134 Ecully Cedex
[b]M.V.Lomonosov Moscow State University, Faculty of Physics, M.V.Lomonosov Moscow State, University,Leninskie Gory, 119991 Moscow, Russian Federation
sebastien.ollivier@univ-lyon1.fr

In the context of the development of MEMS microphones designed for the measurement of high frequency waves and weak shockwaves in air, it is necessary to define new calibration methods in order to estimate accurately the frequency response of new sensors. For this purpose, we will present the principle of a calibration method based on the measurement of weak shockwaves generated by a spark source. The influence of the sources of error will be discussed. To demonstrate the interest of the method, measured responses of 1/8" microphones will be given for various mountings. This work is supported by French National Agency (ANR 2010 BLAN 0905 03) and by French/Russian International Program for Scientific Cooperation PICS (RFBR 10-02-91062/CNRS 5063)

1 Introduction

Different calibration methods are used to calibrate conventional condenser microphones, based on the use of either a reference microphones (in a coupler or in free field), an electrostatic actuation of the membrane, or a pistonphone actuation. These methods are limited to frequencies up to tens of kHz, above which the hypothesis of a uniform pressure applied on the membrane is no more satisfied. In addition, methods based on the electrostatic actuation ot the membrane can be performed only with condenser microphones, and do not applies to piezoelectric or piezoresistive sensors. Most conventional calibration procedures also need to account for geometrical and mechanical parameters of the microphone. Once the microphones have been calibrated, if a special mouting is used then the microphone response at high frequencies is changed, and the frequency response has to be modified using generic corrections. For example some microphone manufacturers provide correction curves at high frequencies to account for the influence of the protection grid.

The present work has been motivated by experimental works on nonlinear propagation of shock waves in complex media, which are based on the use of spark sources [1, 2] This kind of source generates wide band N-waves with front shocks shorter than 1 μs. To perform such experiments, it is needed to caracterise accurately the frequency response of 1/8" microphones at high frequencies for different mountings (with or without the propagation grid, mounted in a baffle, etc.) [3]. For this reason, we have developped a calibration method based on the measurement of N-waves generated by electric sparks. This kind of source, used in nonlinear sound propagation experiments, has been studied experimentally and theoretically [4, 5, 6]. It generates spherical pressure N-waves with duration of the order of 30 μs, front shock rise time of the order of 0.1 μs, and peak pressure level of the order of 2000 Pa at 15 cm. Such waves have significant energy up to 1 MHz, thus it appears that this kind of source can be used to calibrate high frequency MEMS microphones. Some authors have already used spark sources and nonlinear propagation effects to estimate the sensibility of high frequency microphones [4, 7], however, they have not estimated their frequency response. In this paper, we show that the high frequency response of microphones can be estimated from the output voltage resulting from the excitation by the spark generated N-wave without any assumption on the microphone geometry, and for any kind of microphone (condenser, piezoelectric, piezoresistive, ...).

In order to show that the method can be applied to high frequency microphones, the method will first be detailed by simulating the calibration procedure applied to a wide band microphone with a resonant frequency of 300 kHz and a low frequency sensitivity of 1 mV/Pa. Then experimental results will be given for the case of a 1/8" Brüel and Kjær condenser microphone.

2 Method

2.1 Setup

The method is based on the measurement of high pressure level N-waves generated by a spark source. Such source can be either a laser or an electric spark source. We assume that this kind of source has a good reproducibility, and that it can be considered at first approximation as a point source that generates spherical wavefronts. A microphone is placed at a distance r from the source which has to be much larger than the wavelength (figure 1). The output voltage $V(t)$ resulting from the pressure wave is recorded by the microphone (with its appropriate preamplifier) that has to be calibrated.

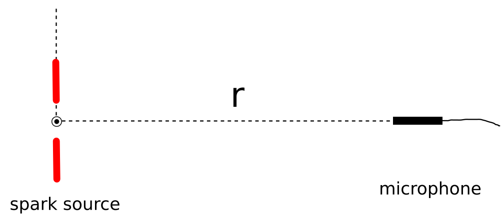

Figure 1: The calibration method is based on the measurement of N-waves at distances r from tens of centimeters to 1.5 cm from a spark source.

In the case of the pressure N-wave plotted in black in figure 2, if a microphone with the frequency response given in figure 3 and a sensitivity of 1 mV/Pa is used, the output voltage $V(t)$ has a distorded shape with oscillations that appears because of the second-order low-pass filtering by the microphone. Another consequence of the low-pass filtering is the huge overestimation of the rise time of the shock, since the voltage rise is mostly governed by the microphone's rise time, and not by the actual pressure rise [6]. Starting from this point, it is considered that both the pressure wave and the microphone response are unknown, and that only the output voltage (the red curve in figure 3) has been recorded at increasing distances r from the source. The closest distance to the source is named r_0. The N-wave pressure level is characterized by the positive peak pressure named P_{max}. The duration is characterized by the time named "half duration" T defined as the time interval between the middle of the front shock and the zero pressure time at the middle of the wave. At $r = r_0$, the positive peak pressure is named P_0, and the half duration is named T_0. Note that the half duration is related to the lowest frequencies of the N-waves, which fall in the frequency range where the sensitivity of the microphone is almost constant. Then it could be assumed that the half duration can be estimated directly from the voltage waveform. However, due to both the increase of the rise time and the oscillations induced by the low-pass filtering, the half duration can not be estimated correctly from the voltage waveform in time domain. A more suitable method is to estimate the half

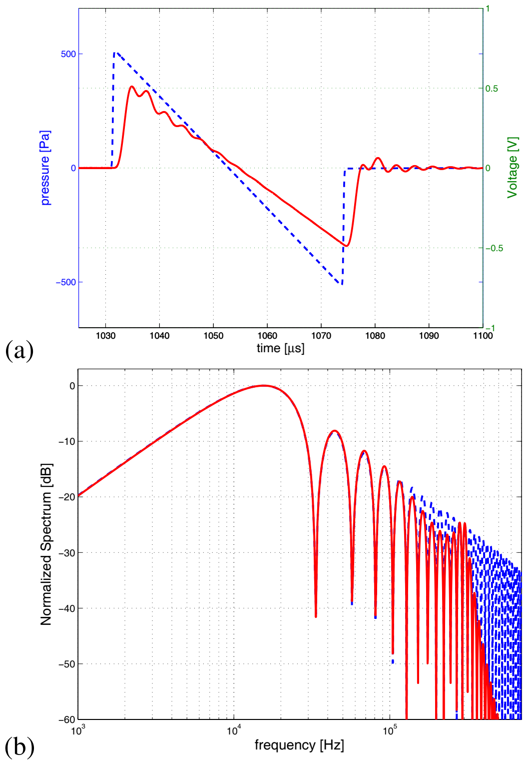

Figure 2: Waveforms and corresponding spectra at 356 mm from the spark source. Blue line: Pressure waveform; Red line: microphone output (microphone frequency response given in figure 3).

duration of the N-wave using its spectrum. As shown in figure 3, the first minima in the pressure and the voltage spectra occur at the same frequencies. Since the frequency of these minima is known for a given waveform (here an N-wave), and since these frequency values depend on the duration of the N-wave, then the half duration can be deduced from the analysis of the spectrum more accurately than from the (distorded) voltage waveform.

2.2 First step: from the voltage to the pressure at $r = r_0$

If a laser or electric spark source is sufficiently powerful, it can generate pressure waves of the order of 2000 Pa or more at 15 cm with a good reproducibility. With such pressure levels, sound propagation is nonlinear, and the duration of and N-wave increases with the distance from the source while the peak pressure decreases. The increase of the duration also depends on the initial pressure level. For a spherical N-wave, weak shock theory gives the following evolution law for the half duration:

$$T(r) = T_0 \sqrt{1 + \sigma_0 \ln(\frac{r}{r_0})}$$

with

$$\sigma_0 = (\gamma + 1) r_0 P_0 / (2\gamma P_{atm} c_0 T_0)$$

where $\gamma = 1.4$ is the ratio of specific heat for gas, $P_{atm} = 10^5$ Pa is the atmospheric pressure, and c_0 is the sound celerity. The coefficient σ_0 shows the dependance of T to the initial peak pressure at $r = r_0$. In order to obtain the coefficient σ_0 from which the pressure level P_0 can be estimated, pressure waves are measured for increasing distances r by

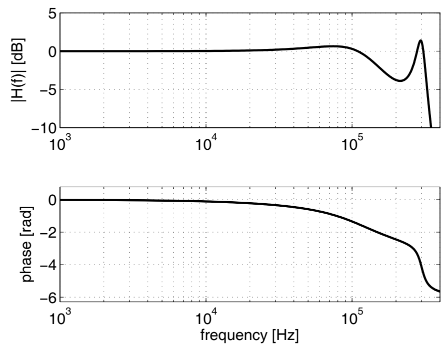

Figure 3: Microphone frequency response. Top: Amplitude response in dB ref. 1 mV/Pa, bottom: Phase response in rad.

the microphone that has to be calibrated, and the voltage signals $V(t, r)$ are recorded. Then the duration $T(r)$ is estimated from the spectrum of $V(t, r)$. To obtain the coefficient σ_0, the parameter $(T/T_0)^2 - 1$ is plotted as a function of $\ln(r/r_0)$, as done in figure 4. The coefficient σ_0 is the slope of the linear function. Note that the uncertainty is here due to the error in the estimation of the frequency of the minima in the spectrum. Once the coefficient σ_0 is obtained, the peak pressure level P_0 is obtained using equation 2.2 as follows:

$$P_0 = \frac{\sigma_0 2\gamma P_{atm} c_0 T_0}{(\gamma + 1) r_0}.$$

At this point, the half duration T_0 and the positive peak pressure P_0 at the distance r_0 are known. Some authors have used this method to estimate the sensitivity of microphones, however, they assumed that the response of their microphones was flat over the measuring range, which was not the case as some oscillations can be seen on their recorded waveforms [4, 7].

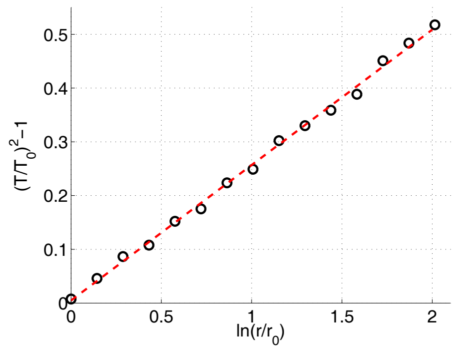

Figure 4: Plot of the volution of the half duration T with the propagation distance in order to estimate the initial pressure level at the distance r_0.

2.3 Second step: frequency response

Assuming that the waveform is an N-wave or any known pressure waveform close to an N-wave, the frequency response of the microphones can be deduced by comparing the theoretical spectrum of the pressure N-wave $P_{th}(f, r)$ and the voltage spectrum $V(f, r)$. A frequency response estimated as the ratio $\tilde{H}(r, f) = V(f, r)/P_{th}(f, r)$ with $r = 356$ mm is plotted in figure 5. It can be seen that the response fits well the response of the microphone amplitude. However, some errors occur at the frequencies that correspond to the minima in the amplitude spectrum because these frequencies for the pressure and the voltage spectra do not perfectly match. In order to estimate more accurately the response at these frequencies, the frequency response can be estimated from the spectra measured at different distances r. The interest is that the frequencies that correspond to the minimum values of the amplitude spectrum are shifted due to the lengthening of the wave induced by nonlinear propagation. This allows to obtain the frequency response for all frequencies. Using a series of estimated responses $\tilde{H}(f,r) = V(f,r)/P_{th}(f,r)$ obtained for 15 distances r from 20 cm to 1.5 m, the frequency response given in figure 6 is obtained. The resulting estimation of $\tilde{H}(f)$ is compared to the frequency response defined in figure 3. The estimated response is close to the microphone response with an error of less than one dB up to 100 kHz, and less than 1.5 dB above 100 kHz. The main source of error in this example is the estimation of the initial pressure wave parameters P_0 and T_0 from the filtered waveforms.

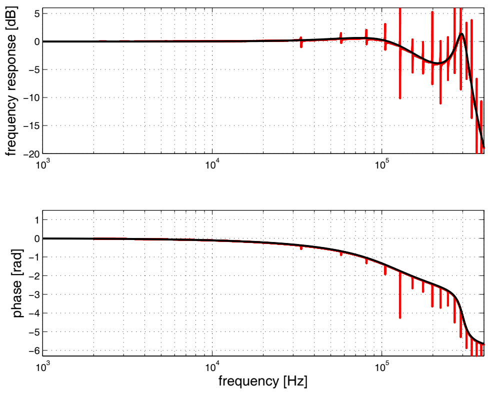

Figure 5: Frequency response $\tilde{H}(r,f) = V(f,r)/P_{th}(f,r)$ estimated from measured and simulation data at the distance r = 356 mm from the spark source.

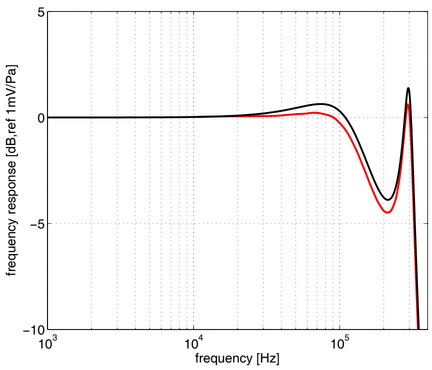

Figure 6: Red line: Amplitude of the frequency response $|\tilde{H}(f)| = |V(f)/P_{th}(f)|$ obtained from a series of recordings at 15 different positions r. Black line: target response $|H(f)|$ given in figure 3.

2.4 Accuracy of the method

A detailed study of the sources of errors is not given here, but some limitations are listed below. The proposed method is based on the hypothesis that the acoustic source is a point source that generates spherical waves. This hypothesis is valid only if the propagation distance r is much longer than the source dimension, which is of the order of the spark gap. The pressure level must be sufficiently high to induce lengthening of the wave due to nonlinear propagation. The method is based on the knowledge of the initial waveform. In the example given in previous section, the wave is assumed to be an N-wave. For a real spark source, a preliminary study has to be done in order to estimate the initial wave parameters (waveform, shock rise time, peak pressure and duration). For this purpose, optical methods can be used. Fluctuations of the peak pressure and of the duration from one spark to another induce errors in the estimation of the amplitude response. The phase response is in addition very sensitive both to the accuracy of the source position, which can vary slightly from one spark to another, and to the temperature value, which influences the travel time of the wave. Finally, the signal to noise ratio limits the accuracy of the estimation of the frequency response at high frequencies.

3 Application to the calibration of 1/8" condenser microphones

The method described in section 2 has been applied in order to calibrate a BrĂźel and Kjær 1/8 inch condenser microphone type 4138 (with its preamplifier) which has been flush-mouted in a baffle, without its protection grid, in order to postpone the diffracted wave. The main difference compared to the procedure described in section 2 is the initial waveform, which is not exactely a symmetric N-wave. It has been estimated using an optical method, based on the analysis of shadowgrams obtained using Schlieren technique. The result of the calibration process is given in figure 7. Since, at first approximation, the incident wave can be considered as a uniform pressure applied onto the membrane, the estimated frequency response (black line) can be compared to the electrostatic actuator response given by the manufacturer in the calibration chart. The two responses do not perfectly match, which is due to both uncertainties, differences in mounting, and filtering by different amplifiers, but the resonance frequency and the cut-off of the microphone's frequency response are well predicted, which demonstrates the interest of the method for the calibration of new sensors for which standard methods do not yet apply. In addition, the "low frequency" sensitivity of microphone (with its preamplifier) obtained using the present method ($\tilde{s}$ = 0.76 mV/Pa) is close to the open-circuit sensitivity given by the manufacturer for this microphone (s_{BK} = 0.82 mV/Pa), which also validates the method.

4 Conclusion

It has been shown that a calibration method based on an N-wave source can be used to obtain the frequency response of microphones at frequencies up to hundreds of kHz, without any assumption on the microphone mechanical or acoustical parameters. This method allows to estimate directly microphones frequency responses for different mountings (with or without grid, flush mounted in a baffle, etc.). It can be applied to any kind of sensor, wathever the trandsuction principle (capacitive, piezoresistive, etc.). This offers the opportunity to calibrate high frequency microphones, including MEMS microphones.

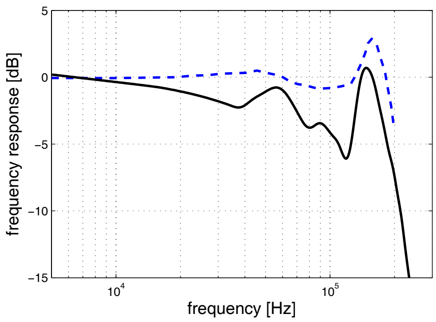

Figure 7: Frequency response of a 1/8 inch condenser microphone (dB, ref. low frequency sensitivity). Black line: estimated frequency response using the proposed method. Blue dash line: frequency response from the calibration chart (electrostatic actuation method).

Acknowledgments

This work is supported by French National Agency (ANR 2010 BLAN 0905 03) and by French/Russian International Program for Scientific Cooperation PICS (RFBR 10-02-91062 / CNRS 5063)

References

[1] M.V. Averiyanov, S. Ollivier, V. Khokhlova, Ph. Blanc-Benon, "Random focusing of nonlinear acoustic N-waves in fully developed turbulence: Laboratory scale experiment", J. Acoust. Soc. Am.,**130**(6), December 2011.

[2] E. Salze, S. Ollivier, P. Yuldashev and Ph. Blanc-Benon, "Laboratory-scale experiment for the propagation of N-waves in a turbulent and refracting medium with ground Effects", ACOUSTICS2012/633

[3] S. Ollivier, E. Salze, P.V. Yuldashev, and M.V. Averiyanov. "Mesure d'ondes de choc acoustiques: influence de la réponse des microphones". In 10ème Congrès Français d'Acoustique, Lyon France, 2010. http://hal.archives-ouvertes.fr/hal-00542879/en/.

[4] W.M. Wright, "Propagation in air of N-waves produced by sparks", J. Acoust. Soc. Am., **73**, 1948-1955 (1983).

[5] P.V. Yuldashev, M.V. Averiyanov, V.A. Khokhlova, S. Ollivier, and Ph. Blanc-Benon, "Nonlinear spherically divergent shock waves propagating in a relaxing medium", Physical Acoustics, 54(1):32-41, 2008.

[6] P.V. Yuldashev, S. Ollivier, M. Averiyanov, O. Sapozhnikov, V. Khokhlova, and Ph. Blanc-Benon, "Nonlinear propagation of spark generated N-waves in relaxing atmosphere: modeling and measurements using acoustical and optical methods", J. Acoust. Soc. Am., 120(3):29-34, 2010.

[7] B. Lipkens and D.T. Blackstock, "Model experiment to study sonic boom propagation through turbulence. Part I: general results", J. Acoust. Soc. Am., **103**(1):48-158, 1998.