Acoustic Behaviour of a Corona Loudspeaker with High Electric Modulations

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This paper presents the acoustic behaviour of a negative point–to–plane corona loudspeaker. The electrode gap is divided into an "ionisation" region and a "drift" region. In each region, interactions between charged and neutral particles lead to a perturbation of surrounding air and so generate an acoustic field. An acoustic modeling and an experimental set-up measuring acoustic frequency responses with high electric modulations have been developed. Good agreement is obtained between predicted and measured pressures ; and a nonlinear acoustic behaviour have been also observed.

INTRODUCTION

Inside a corona loudspeaker, air is ionised by applying a high voltage between electrodes having different curvature radii (a needle facing a plane in our case). The complex phenomena due to collisions between particles inside the electrode gap are called discharges in the gas, or when a glow appears, corona discharges. Modulating the electric field, an acoustic wave results from the interactions of charged and neutral particles of the ionised gas. The main objective of this paper is to describe the acoustic behaviour of the ionised gas with high electric modulations.

ELECTRIC BEHAVIOUR

A corona discharge occurs at a certain voltage ($V_s \approx 2kV$) between electrodes. Because of the geometric effect and the local presence of charged particles, the electric field in the gap is strongly non-uniform. The ionised gas does not follow Ohm's law and displays a nonlinear current–voltage curve (fig. 1). Although the negative corona discharges are rather complex phenomena, the quadratic empirical relationship between the current and the voltage, often used for small gap distances ($d \leq 1$cm), is

$$I = \kappa(V - V_s)^2, \qquad (1)$$

where κ is a constant which depends on the geometric configuration and gas parameters [3]. Considering a time-averaged repartition of the electric field in the gap, two regions are distinguished : the "ionisation region", located at the tip of the point, where the electric field amplitude is high, and the "drift region", between the ionisation region and the plane electrode, characterised by a weaker and almost uniform value of the electric field. The dynamic behaviour of the ionised gas is modeled by an electric equivalent circuit with three parameters ($r_i \approx 1\text{M}\Omega$, $r_u \approx 10^5\Omega$, and $C_u \approx 0,25$pF, see fig. 1, [1, 2]).

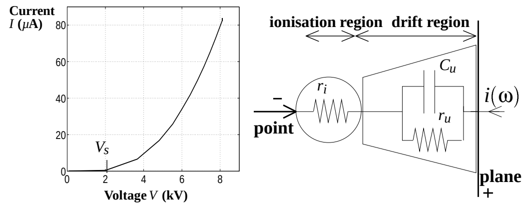

FIGURE 1. Current–voltage curve and schematic representation of the point-to-plane loudspeaker.

LINEAR ACOUSTIC BEHAVIOUR

The interaction mechanisms between charged and neutral particles involves both collisional-momentum and thermic energy exchange effects which are introduced in the acoustic equations by two source terms : a force source and a heat source. From the classical linear equations in acoustics, two Helmholtz's equations respectively associated with each type of source are deduced [1] :

$$\left(\Delta + \left(\frac{\omega}{c_0}\right)^2\right) p_f(\vec{r},\omega) = \nabla f(\vec{r},\omega), \qquad (2)$$

$$\left(\Delta + \left(\frac{\omega}{c_0}\right)^2\right) p_h(\vec{r},\omega) = -j\omega\frac{\gamma-1}{c_0^2} h(\vec{r},\omega) \qquad (3)$$

where γ, c_0, ω, and $\vec{r}$ are respectively the constant specific-heat ratio, the adiabatic sound speed, the pulsation, and the observation distance. The acoustic pressures p_f and p_h are respectively associated with the average volumic force f applied by the charged particles on the neutral particles, and with the thermic power h dissipated per unity of volume. Considering the ponctual geometry of the heat source and the cylindrical geometry of the force source, acoustic pressures are obtained by calculating the integral solution of eq. 2 and eq. 3 with the free space Green function $G(|\vec{r}-\vec{r_0}|,\omega) = \frac{e^{j\left(\frac{\omega}{c_0}\right)|\vec{r}-\vec{r_0}|}}{4\pi|\vec{r}-\vec{r_0}|}$. With low frequencies and far field conditions, the acoustic pressures are written :

$$p_f(\vec{r},\omega) \approx A_f \cos\theta \frac{e^{-j\left(\frac{\omega}{c_0}\right)r}}{r} i(\omega), \qquad (4)$$

$$\text{with } A_f \approx \frac{1}{4\pi\mu_i(\beta+1)} \frac{j}{(1+j\omega r_u C_u)} \left(\frac{\omega}{c_0}\right) d, \qquad (5)$$

where μ_i is the negative ions mobility, $\beta = I_e/I_i$ is the ratio of the electronic and ionic components of the current, and θ is the observation angle from the point axis ; and

$$p_h(r,\omega) \approx \left(\frac{j(V_i - V_a)}{4\pi} \frac{\omega}{c_0} \frac{\gamma-1}{c_0}\right) \frac{e^{-j\left(\frac{\omega}{c_0}\right)r}}{r} i(\omega), \qquad (6)$$

where $(V_i - V_a)$ is the voltage applied to the ionisation region. The acoustic pressure response measurements are in agreement with the theoretical predictions (see fig. 2). The total acoustic pressure $(p_h + p_f)$ displays a 6dB/oct. slope interrupted at high frequencies by the influence of the capacity C_u. High electric modulations allow to study the acoustic behaviour of the transducer at low frequencies (in the order of few hundred hertz) since the acoustic pressure is higher than the back noise level induced by the global gas flow. In that frequency domain, the slight discrepancy between predicted and measured results is reduced by modeling the source force with a truncated conical volume (owing to the complicated form of the expression, the formula is not reproduced here).

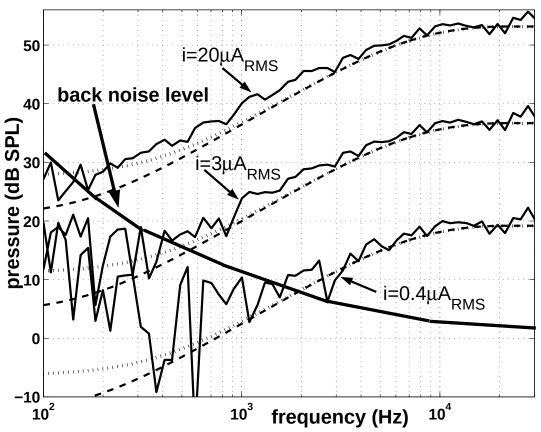

FIGURE 2. Frequency responses of the point-to-plane loudspeaker. ($I = 60\mu A$, $d = 6mm$, $r = 30cm$). Theoretical predictions : force source with a cylindrical volume (eq. 4) (- - -), and with a truncated conical volume (....).

With high electric modulations up to $i = 20\mu A_{RMS}$ with $I = 60\mu A$ (modulation ratio of 33%), theoretical and experimental results are in agreement. However, the total current (DC+AC) is limited by the current values corresponding to the onset and the disruptive (when electric sparks occur) voltages. This precaution avoids parasite noise production.

NONLINEAR ACOUSTIC BEHAVIOUR

Althougth a current drive with a very low distorsion rate is used for the electric modulation, the acoustic pressure has high harmonic components (see fig. 3). The total harmonic distorsion is estimated to be arround 10%. The

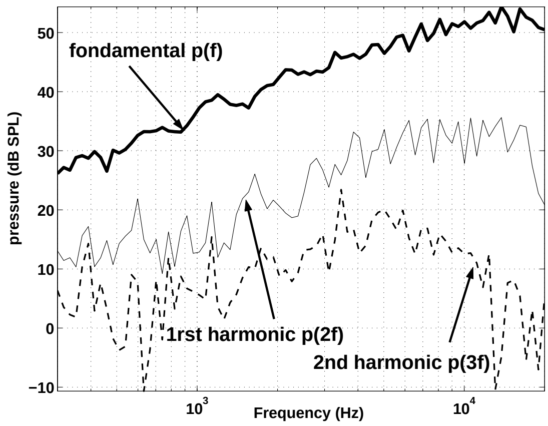

FIGURE 3. Sound pressure level of the harmonics ($I = 60\mu A$, $i = 20\mu A_{RMS}$, $d = 5mm$, r =30cm).

corona loudspeaker presents a nonlinear behaviour which cannot be avoided by using a current drive although it is more adequate than the voltage drive which would exhibit the intrinsically quadratic behaviour on the fondamental frequency component of the pressure (see fig. 1). The acoustic modeling have to be completed by taking into account the nonlinear contributions which are mainly due to the heat source.

REFERENCES

1. Ph. BÉQUIN & al. Modeling of Negative Point–to–Plane Corona Loudspeaker. *J. Eur. Phys.: Appl. Phys.*, 2001, accepted.
2. M. M. KEKEZ & al. *J. Phys. D: Appl. Phys.*, 15:1963–1973, 1982.
3. G. F. LEAL FERREIRA & al. *J. Appl. Phys.*, 59(9):3045–3049, 1986.