Characteristics of a spark discharge as an adjustable acoustic source for scale model measurements

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The simulation of acoustic phenomena using urban street scale models requires the use of a small and powerful sound sources with a wide frequency bandwidth and omnidirectional radiation. Among different source types able to provide these characteristics, spark discharge in air is an interesting solution. The principle is based on the generation of an electric discharge by applying a high voltage between two electrodes. First the gas becomes electrically conducting, the electric current heats up the gas, causing the formation of an impulsive sound signal. These sources have been also widely used for shock wave propagation, like sonic boom, for which propagation is non linear. However, the behaviour of spark discharges and their acoustic radiation depend greatly on the electrodes gap. Very little investigation has been done of this dependance; this work provides a characterisation of a spark discharge in function of the electrodes gap. Electrical characteristics, pressure profiles, radiations are studied in function of various spark gaps. This experimental study is meant to be a useful resource for experimenters to design a spark discharge adapted to their specific applications.

1 Introduction

Scale models can be of great help for studying physical phenomena in the domains of room acoustics and urban acoustics. The simulation of acoustic phenomena using scale models requires that all dimensions be scaled down in length. This is readily done for physical structures, such as buildings, streets. Since the air surrounding the model cannot be scaled down, the wavelengths of the sound waves must be scaled down by increasing the frequency of the source. Thus, in a study using a $1 : n$ scale model, a 1 kHz acoustic wave would increase by a factor of n, to $n \times 1$ kHz, to maintain proportionality. Consequently, the simulation of acoustic phenomena using street scale models requires the use of small sound sources with a wide frequency bandwidth. A variety of sound sources such as air-jet and electro-acoustic sources, laser-generated acoustic pulses and electric sparks have been used, depending on the scale-modeling application. Electric sparks in air are small and powerful sound sources with a wide frequency bandwidth and omnidirectional radiation. Many investigations of spark have been carried out in the past (see for example [2] [3] [17] [14]). However, the behaviour of spark discharges and their acoustic radiation depend greatly on the electrodes gap. Very little investigation has been done of this dependance ; this paper provides a characterisation of a spark discharge in function of the electrodes gap.

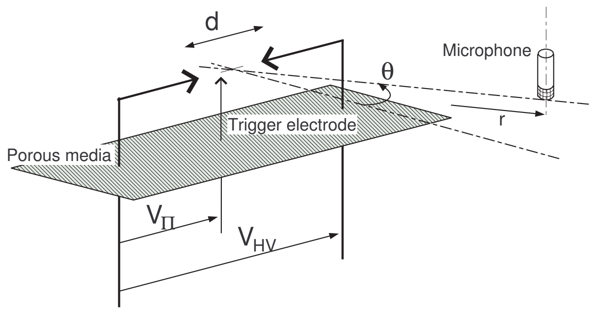

Figure 1: Schematic representation of a three-electrodes system for the generation of sparks and the experimental set-up used for the measurement of acoustic waveform. V_{Π} and V_{HT} are the trigger voltage and the capacitor voltage; d and r are the gap length and the distance from the centre of the discharge.

2 Generation of spark discharges

The sparks were produced by applying a high voltage between a short point-to-point gap in air at atmospheric conditions (figure 1). Experiments were performed using a "three-electrodes system" in which the storage capacitor (a bank of $10 \times 22\mu F$ capacitors in series) was kept charged at a voltage (up to $20\,kV$) lower than the breakdown voltage V_b of the gap. The two horizontal point electrodes are in tungsten with a diameter of $2\ mm$, the gap could be varied from $0 - 2\ cm$. A third electrode is placed between the main electrodes to provide an initial ionisation of the air necessary to cause the spark breakdown mechanism and the discharge of the capacitors.

Voltage measurements were made with a high-voltage probe (1000:1) placed at the high-voltage electrode and the current I flowing through the spark discharge was measured with an adapted current probe. Figure 2 shows the measured data associated with breakdown voltage V_b and the maximum current I_{Max} versus the gap length d. The observed evolutions clearly indicate that V_{Π} and I_{Max} have a linear dependence on gap length d. However, due to the electronic system, a saturation of the current is observed for d greater than 16 mm.

The electrical energy input to the discharge was estimated from the energy stored in the capacitors : $E = \frac{1}{2}CV^2$ where $V = V_b$ is the voltage across the capacitor C in the electrical circuit ; this energy is evaluated between 10 and 700 mJ. The electrical energy deposited in the gap is dissipated as ionisation energy, dissociation energy of molecular gases, thermal energy and mechanical expansion. The electro acoustic efficiency is estimated to be less than 10% [7] [3] [2].

During the discharge, due to ionisation processes, a channel of ionised gas is formed between the electrodes. The channel expands as a result of the intense Joule heating. The gas channel radiates an intense shock wave that promptly transforms into an acoustic pressure pulse that propagates into the surrounding medium at the local speed of sound.

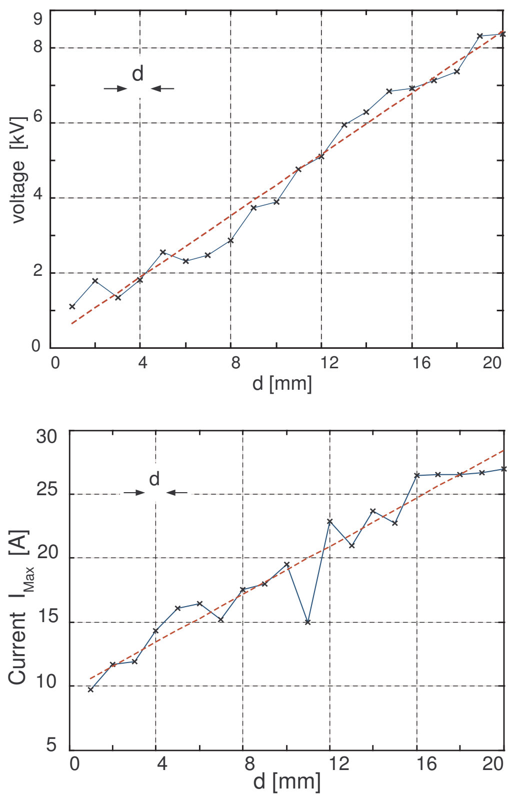

Figure 2: Voltage V_{Π} associated with spark breakdown and current I_{MAX} versus the gap length d. Dashed lines are least square fits to the data.

3 Acoustic of spark discharges

A 1/8 *in.* condenser microphone (G.R.A.S.) associated with an amplifier (NEXUS) was used to measure the acoustic pressure generated by the spark. The microphone was oriented at 90 angle to the point-to-point axis of the spark (figure 1). This orientation is usual to make measurements in the volume of a scale model. The protective grid was kept on for all pressure time measurements. This grid affected the free field response characteristics of the microphone due to the amplification of the higher frequency components of the pressure wave caused by wave diffraction about the grid. In this work, the frequency range was limited to 100 kHz which is usual for room or urban acoustics scale model measurements. To establish repeatability, each measure was run 40 times and the standard deviation of the pressure measurements do not decrease significantly with a greater measurements number. The measurements have been performed for distances r (spark-microphone) from 0.1 up to 3.2 m in an anechoic chamber.

3.1 Pressure waveforms

Figure 3 shows the typical pressure curves associated with various gap lengths. Due to the filtering effects (low frequency response) of the microphone, the details associated with the fast rising portion of the shock wave and particularly the peak-pressure value are distorted. The rise time T_r of the microphone is measured around 7 μs [8] [14]. After the initial pressure rise the overpressure turns slowly to zero, the time being related to d the

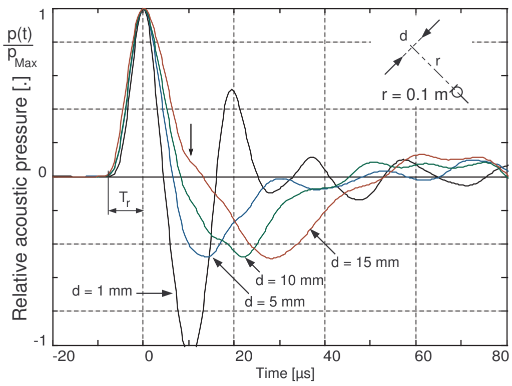

Figure 3: Pressure ratio $p(t)/p_{Max}$ versus time at $r = 0.1\ m$ from the spark for various gap lengths.

length of the gap. This part is affected by the diffraction on the protective grid (see the artifact around 12 μs). The waveforms associated with the higher gap length have smaller rarefaction amplitudes and a longer rarefaction durations.

3.2 Empirical waveforms

N-wave is frequently used to describe the pressure signature of sparks. However, this model poorly represents the rarefaction phase of the actual waveforms. Calculations (numerical integration of the gas dynamic equations with initial conditions and equations of state [10] [12]) for moderate shock wave do provide pressure signatures that are quite adequately verified by measurement. Once established, these signatures are fairly well preserved to small distances from the source [11]. These signatures are approximated by

$$p(t) = P_{Max}\left(1-\frac{t}{t_+}\right)\left(1-\frac{t}{\tau}\right)\left(1-\left(\frac{t}{\tau}\right)^2\right) \qquad (1)$$

where t_+ is positive phase duration (compression), P_{Max} is peak shock overpressure and τ is total wave duration.

Figure 4 shows the experimental waveform measured at the distance $r = 0.1\ m$ from a spark with gap length $d = 5\ mm$, the initial waveform (Eq. 1), and the initial waveform filtered with a low pass-filter which is an idealised model of a measuring system (microphone and amplifiers) [13] [14]. After filtering, the waveform with an infinitely small rise time and a high peak-pressure transforms to a waveform with a shape similar to the experimental pressure signature. The oscillating disturbances before the shock front are due to the filtering artifacts.

3.3 Overpressure measurements

Figure 5 shows the overpressure P_{Max} versus the gap length for various values of the distance r between the microphone and the axis of the electrodes. Whatever the distance r, the curves P_{Max} versus d present similar form. From these experimental results, two particular evolutions are observed : for $d < 4\ mm$, the overpressure P_{Max} follows a $d^{\simeq\frac{1}{5}}$ dependence and for $d > 4\ mm$,

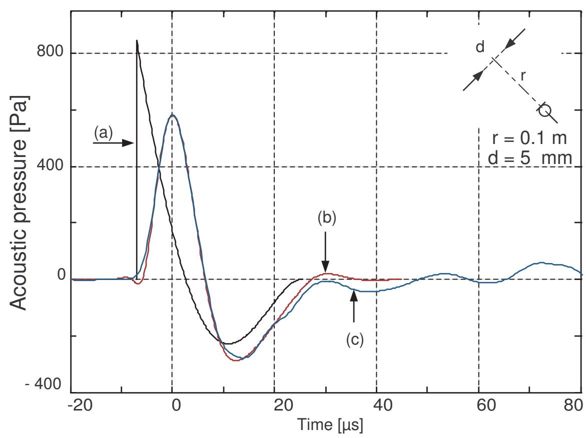

Figure 4: Acoustic pressures $p(t)$ versus time. **(a)** Initial waveform (Eq. 1) with $P_{Max} = 848.25\ Pa$, $t_+ = 9.6\ \mu s$ and $\tau = 32.5\ \mu s$. **(b)** Effect of low pass filtering on Initial waveform (low-pass filter with cut-off frequency $f_c = 62\ kHz$ and attenuation 0.45 s). **(c)** Measured pressure at $r = 0.1\ m$ of a spark discharge with $d = 5\ mm$.

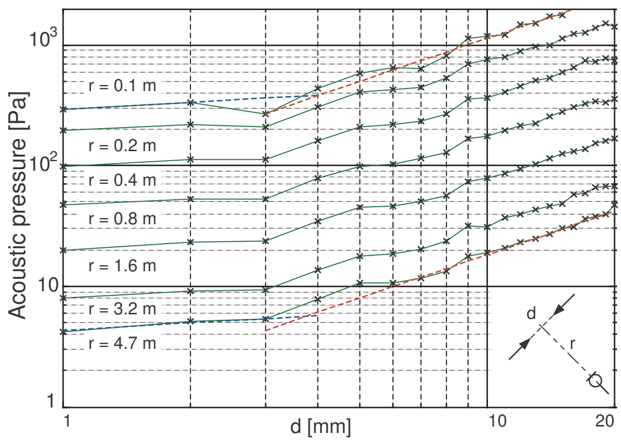

Figure 5: Overpressure P_{Max} versus gap length d at various distances r.

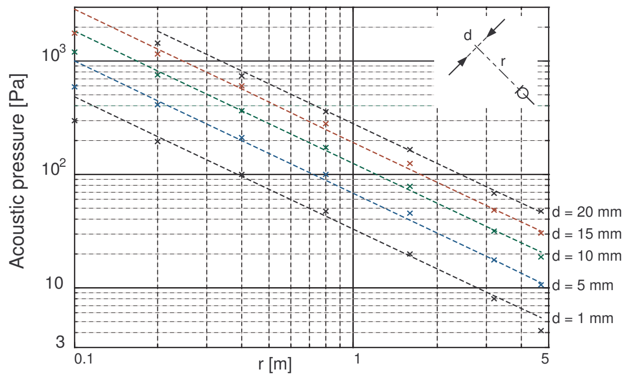

Figure 6: Overpressure P_{Max} versus distances r for various distances gap length d.

P_{Max} follows a $d^{\simeq \frac{6}{5}}$ dependence. Since d is related to the energy released in the spark, two different types of sparks are observed.

Figure 6 shows that, whatever the gap length d and beyond a distance r of 0.2 m, the overpressure decay follows a $r^{-\frac{7}{6}}$ dependence (dashed lines). Theory associated with spherical shock of weak strength [15] gives that overpressure P_{Max} is proportional to $\left[r\left(\ln r\right)^{-\frac{1}{2}}\right]^{-1}$ which can be approximate by $r^{-\frac{7}{6}}$. Consequently, weak-shock theory can be used for propagation of these waves. Numerical simulations (time-domain code) of finite amplitude propagation which include the combined effects of nonlinearity, dispersion and geometrical spreading can be used to deduce the final waveforms [16] [14].

3.4 Directivity

Figures 7 and 8 show two polar diagrams for $d = 5\,mm$ and $d = 20\,mm$. The spark source is not perfectly omnidirectional for small gap length (5 mm) and not too directional for large gap (20 mm). The overpressure P_{Max} is reduced at 90° of 2.5 dB and 4.4 dB respectively for $d = 5\ mm$ and $d = 20\ mm$. Wright et al. [17] consider a uniform distribution of acoustic point sources, which radiate N-waves in phase and without interaction, along a straight line of length d. Comparisons between our experimental data and the predictions of this model are not satisfactory.

4 Conclusion

The electrical spark source is one solution for measurements in scale models. The spark source is quite small (electrodes gap lower than 20 mm), can be powerful (up to 140 $dB\ SPL$ at 1 m from the source). The spark source is quite omnidirectional.

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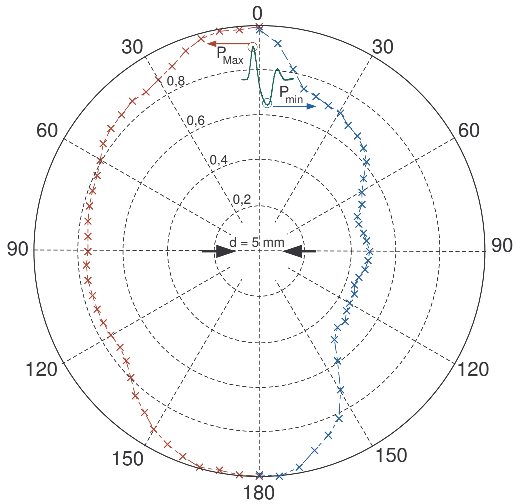

Figure 7: Angular dependence of the overpressure P_{Max} and the rarefaction pressure P_{min}. Spark with $d = 5\ mm$.

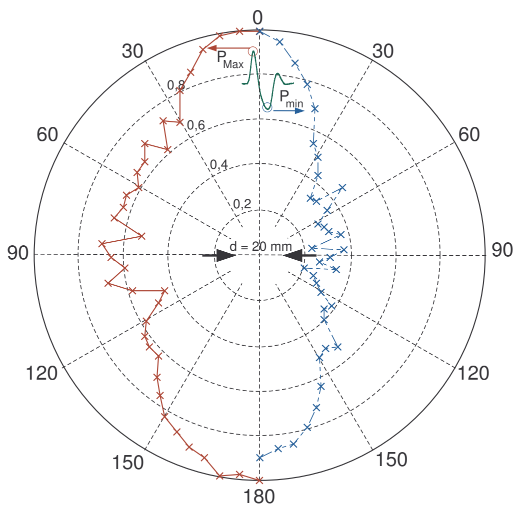

Figure 8: Angular dependence of the overpressure P_{Max} and the rarefaction pressure P_{min}. Spark with $d = 20\ mm$.

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