Sound sources with corona discharges*

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A study has been made of three sound sources, each of which is constructed out of a plane wire gauze (positive electrode) and a great many needles (negative electrode) pointing toward it. Direct current coronas have appeared when a high dc potential has been applied to the sound sources in the atmosphere. Various experiments have been performed on the acoustical characteristics of the sound sources as they are supplied with an ac current in the frequency range of 0.2–10 kHz, which is superposed on a dc current. The sound sources are each considered as consisting of a resistance shunted by a capacitance, so far as the ac current is concerned. Theoretical formulas are obtained from the assumption that the sound is produced by a vibratory force which acts directly on the air between the electrodes and which has an rms value $(d/b)I'$, where d is the gap length, $b = 2.2\ \mathrm{cm^2/V\text{-}sec}$ and I' is the rms value of an ac current through the resistance. It has been found the experimental results for 0.2–1 kHz are in good agreement with the calculated ones obtained from the formulas.

Subject Classification: 14.7; 11.5; 7.8.

INTRODUCTION

It has been known that sound is generated by means of a corona produced by a high-frequency or dc voltage when it is modulated by a signal.[1–6] In the case of dc voltage, the sound source has been constructed out of two or three electrodes. This paper is particularly concerned with the sound source of two electrodes supplied with dc and signal voltage. A number of researches have been known concerning this type of sound source.[3,4] Although they deal extensively with noise, corona wind, ozone, and particular applications as well as with sound production, these researches do not seem to be quite satisfactory about details of the acoustical characteristics of sound sources (for example, directivity, effect of dc current).

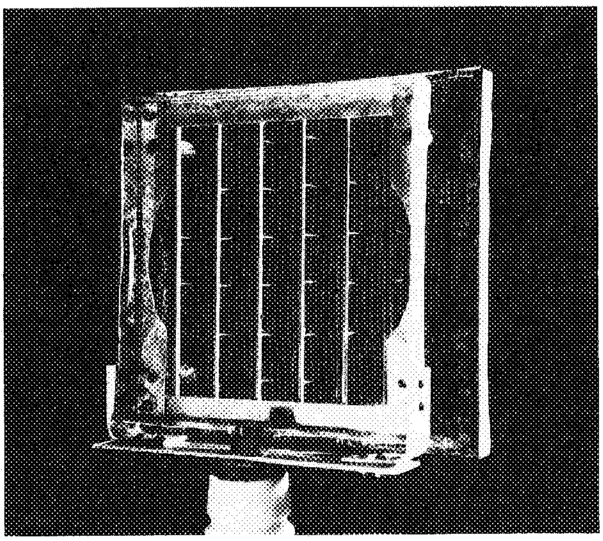

Fig. 1. Sound source 1.

We shall describe below the experimental results concerning the sound produced by our sound sources. We shall also present some related theoretical formulas, which are in good agreement with the experimental results for low frequencies.

I. CONSTRUCTION AND DC CHARACTERISTICS

We built three sound sources which were different from each other in constructional details. They are specified in Table I and one of them is shown in the photograph of Fig. 1. The positive electrode of each is a flat brass-wire gauze; the negative electrode is made of a great many steel needles which are placed equidistant from each other so as to be distributed within a circle of radius a; the needles have points which are about 0.05 mm in radius of curvature. The sound sources each consist of the two electrodes with an air gap (length d) between them. The needles are perpendicular to the wire gauze.

The dc voltage–current characteristic curves of the sound sources are shown in Fig. 2. The coronas appearing between the electrodes of one of the sound sources are shown in the photograph of Fig. 3.

Table I. Constructional details of sound sources.

	Positive electrode		Negative electrode			
Sound source	Diameter of wires (mm)	Spacing of wires (mm)	Number of needles	Distance between adjoining needles (mm)	Effective radius a (mm)	Gap length d (mm)
1	0.6	4.3	24	26	66	9.6
2	0.2	1.7	120	12	72	19.2
3	0.6	4.4	120	12	72	10.2

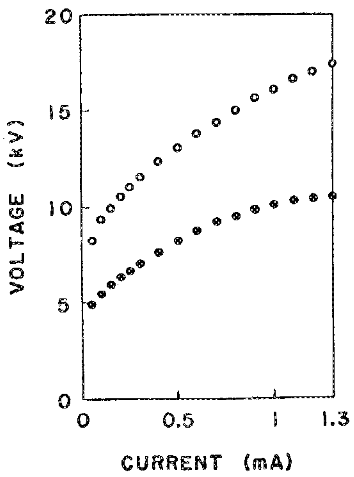

FIG. 2. Direct current voltage-current characteristics. ●: sound source 1. ○: sound source 2.

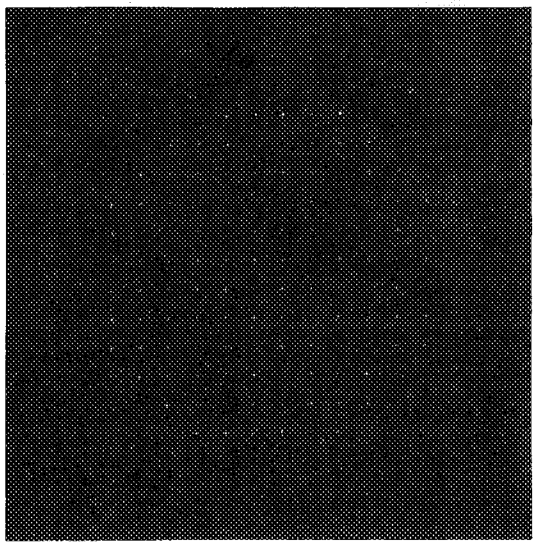

FIG. 3. Coronas of sound source 2, for dc voltage 18 kV and dc current 1.5 mA.

II. EXPERIMENTAL METHODS

The circuit for the sound sources is shown schematically in Fig. 4. The maximum output of the high-voltage dc source was 35 kV×1 mA. The sound sources were each supplied with a dc current I_0 on which was superposed an ac current of rms value I. In order that the ac current might be sinusoidal, experiments were made within the range of $2I \leq I_0$. The frequency range of the ac current was 0.2–10 kHz.

Each one of the sound sources was fixed to an immovable support which had an arm that could be rotated around it. To the arm was attached a Brüel & Kjær type 2203 precision sound level meter with a type 1613 octave filter set. The distance between the microphone and the center of the sound source was 25 or 50 cm. The sound level meter was calibrated with a type 4220 pistonphone. Directional patterns of the sound sources were recorded by means of a conventional X–Y recorder.

All the apparatuses were set in an anechoic room which had the inner dimensions of 4.6 m×3.1 m×2.6 m.

III. THEORETICAL DISCUSSIONS

We assume that the sound source is a resistance R shunted by a capacitance C so far as the ac current is concerned, where R is the slope of the dc voltage–current characteristic curve and C is the sum of the capacitance of the sound source itself and the stray capacitance of the plate circuit of the vacuum tube. The rms value I' of an ac current through R is expressed as

$$I' = I[1+(\omega CR)^2]^{-\frac{1}{2}}, \tag{1}$$

where ω is the angular frequency.

We introduce a vibratory force which, corresponding to the ac current through R, has the angular frequency ω and the direction perpendicular to the wire gauze. The force is considered to act directly on the air between the electrodes. For its rms value F, we may have

$$F = (d/b)I'. \tag{2}$$

This equation should hold good and b would be the mobility if we were able to assume the absence of positive ions, a constant mobility value, and a much shorter transit time of charged particles than $2\pi/\omega$, for the discharge region between the electrodes (excepting the small parts of violent discharge about the points of the needles).[7] But this assumption is not likely to apply to our case. In Sec. IV, therefore, we shall discuss b on the basis of experimental results.

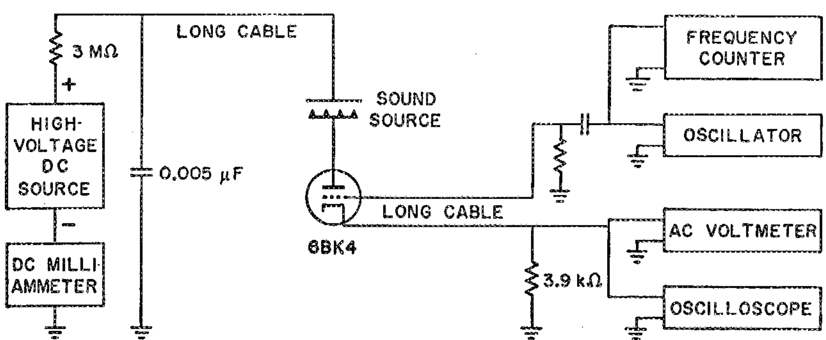

FIG. 4. Schematic diagram of the circuit for sound sources.

The vibratory force produces the sound pressure of angular frequency ω. If its rms value is denoted as P at distance r from the sound source in the direction perpendicular to the wire gauze, P is given by[8]

$$P=F\frac{\omega}{4\pi r V}\left[1+\left(\frac{\lambda}{2\pi r}\right)^2\right]^{\frac{1}{2}}, \tag{3}$$

where V is the sound velocity and λ is the wavelength. In Eq. 3, it is assumed that $(r^2+a^2)^{\frac{1}{2}}-r$ is much smaller than both λ and r.

From Eqs. 1–3, we obtain

$$P=\frac{d}{b}\frac{I}{4\pi r V}\left[1+\left(\frac{\lambda}{2\pi r}\right)^2\right]^{\frac{1}{2}}\frac{\omega}{[1+(\omega CR)^2]^{\frac{1}{2}}}. \tag{4}$$

The sound pressure decreases from P to P' if we shunt the sound source with a capacitance C'. From Eq. 4, we obtain

$$\frac{P}{P'}=\left\{\frac{1+[\omega(C+C')R]^2}{1+(\omega CR)^2}\right\}^{\frac{1}{2}}. \tag{5}$$

A formula for the directivity can be obtained if we assume that the force is uniformly distributed over the circular region of radius a between the electrodes. Each small part of the source has a directivity proportional to $\cos\gamma$,[8] where γ is the angle which specifies the direction and $\gamma=0°$ means the direction in which the needles point. Therefore, the sound-pressure ratio D for the sound source is given by

$$D=|[2J_1(z)/z]\cos\gamma|,$$
$$z=(2\pi a/\lambda)\sin\gamma, \tag{6}$$

where $J_1(z)$ is the Bessel function.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Second Harmonic and Linearity

The second harmonic of the sound pressure was at least 20 dB below the level of the fundamental component. The sound pressure was proportional to the ac current through the sound source in each of our experiments.

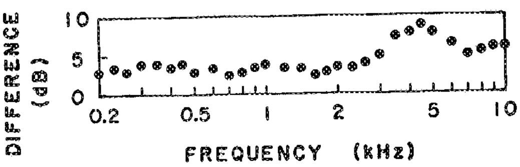

Fig. 5. Difference in sound pressure produced by sound source 3 in the directions $\gamma=0°$ and $\gamma=180°$, for $I_0=0.75$ mA.

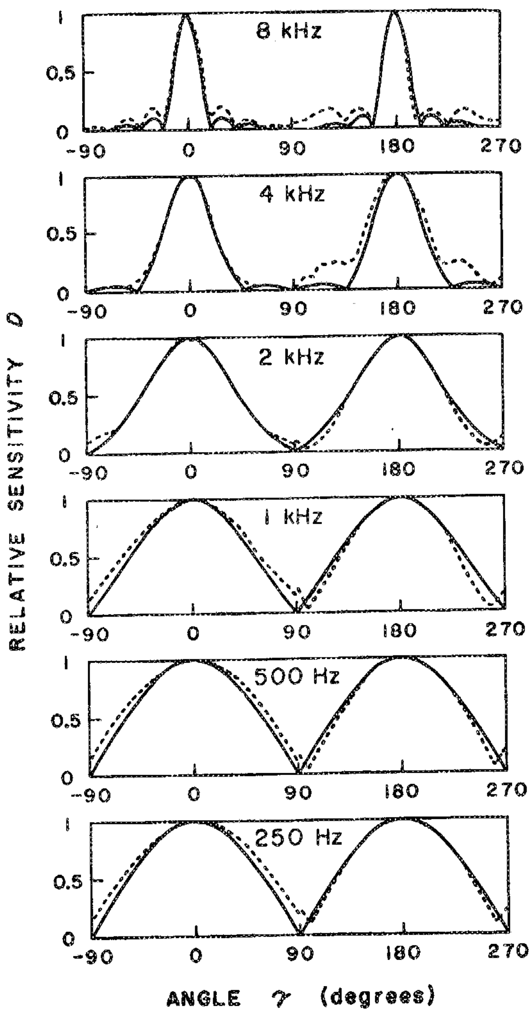

Fig. 6. Directional patterns of sound source 3, for $I_0=0.75$ mA. - - -: experimental; ———: calculated from Eq. 6.

B. Directivity

The sound pressure was larger in the direction $\gamma=0°$ than in the direction $\gamma=180°$, as shown in Fig. 5. But the difference was small (2–6 dB) below 2 kHz for every one of the three sound sources.

The experimental directional patterns of sound source 3 are shown in Fig. 6 by broken-line curves. For $-90°\leq\gamma\leq 90°$, the sensitivity of the recorder was so adjusted that the maximum value of those curves about $\gamma=0°$ was 1. For $90°\leq\gamma\leq 270°$, it was so adjusted that the one about $\gamma=180°$ was 1. The calculated values of D are obtained from Eq. 6 and are shown by the solid line in Fig. 6. The experimental curves are in good agreement with the calculated ones. The results for sound sources 1 and 2 are similar to those for sound source 3.

It may be concluded that below 2 kHz the experimental directivities are in good agreement with the calculated ones.

The calculated D is nearly equal to $|\cos\gamma|$ below 1 kHz, and is considerably influenced by $\cos\gamma$ at 2 kHz. Nondirectional phenomena, such as harmonic thermal expansion, have only a slight effect on the pattern of radiated sound below 2 kHz.

C. Effect of Shunting Capacitance

Experiments were made on the decrease in sound pressure caused by connecting a known condenser in parallel with the sound source at $I_0=0.75$ mA. The results, which were the same in two directions $\gamma=0°$ and $\gamma=180°$, are shown in Fig. 7 by using dots. The calculated solid-line curve in Fig. 7 is obtained from Eq. 5, where certain values of C and R are used in order that the curve may be in the best agreement with the dots. These optimum values are shown in the second and third columns of Table II. On the other hand, the values of R at $I_0=0.75$ mA are directly obtained from the dc characteristic curves in Fig. 2, and are listed in the fourth column of Table II. The two sets of values for R are in good agreement with each other. The curve agrees well with the dots up to 10 kHz, as shown in Fig. 7. But it is difficult to decide whether the R value is suitable for Eq. 4 at high frequencies because Eq. 5 reduces to $P/P'\simeq(C+C')/C$.

It may be concluded that R, the resistance at zero frequency, is valid for Eq. 4 at least up to 1 or 2 kHz.

D. Dependence upon Direct Current

The variation in the sound pressure was examined as a function of I_0 for the range 0.15–1 mA with the ac current constant. The results in the directions $\gamma=0°$ and $\gamma=180°$ agreed fairly well with each other. The means of the data in the two directions are plotted in Fig. 8. This figure shows that the sound pressure is almost independent of I_0 below 1 kHz, and it is ascertained that the same thing can be said of sound sources 1 and 3.

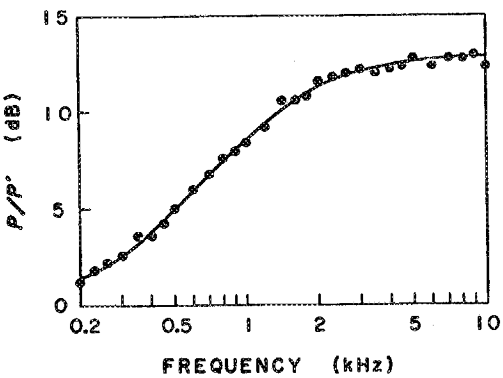

FIG. 7. Decrease in sound pressure caused by connecting a condenser $C'=96$ pF in parallel with sound source 1 at $I_0=0.75$ mA. ●: experimental; ———: calculated from Eq. 5.

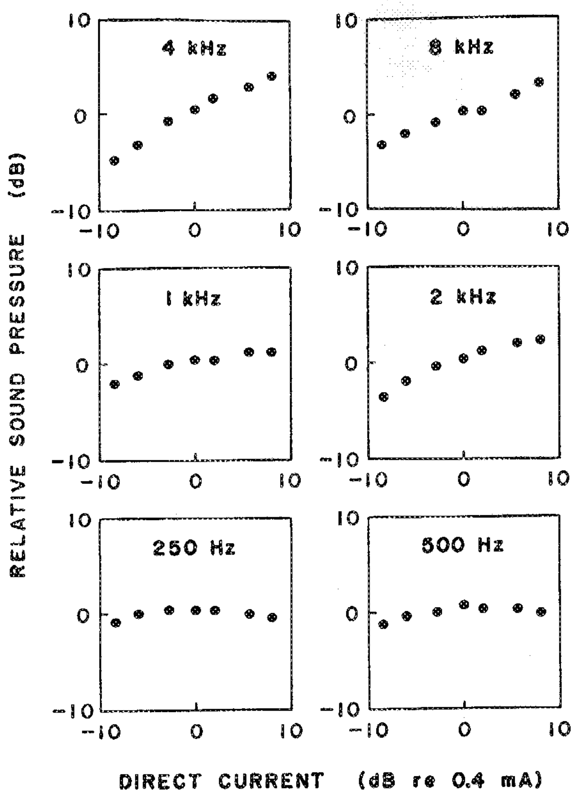

FIG. 8. Variation in sound pressure produced by sound source 2 as a function of dc current ranging from 0.15 to 1 mA.

On the right side of Eq. 4, both b and R may depend upon I_0. The value of R is estimated on the basis of the curves in Fig. 2. The variation in $[1+(\omega CR)^2]^{\frac{1}{2}}$ is less than 2 dB at 500 Hz and less than 5 dB at 1 kHz for $0.15\text{ mA}\leq I_0\leq 1$ mA. Therefore, it may be concluded that b is independent of I_0 below 500 Hz. At 1 kHz, although the experimental sound pressure increases by a small amount with increasing I_0, there is some increase due to the R variation on the right side of Eq. 4. Accordingly, b is almost independent of I_0 at 1 kHz.

E. Frequency Response

The means of the experimental sound pressures in the directions $\gamma=0°$ and $\gamma=180°$ were obtained as a function of frequency for $I_0=0.75$ mA, $I=0.38$ mA, and $r=50$ cm. They are shown in Fig. 9 by using dots.

TABLE II. Resistance and capacitance of sound sources.

Sound source	Capacitance C from Eq. 5 (pF)	Resistance R at $I_0=0.75$ mA: from Eq. 5 (MΩ)	Resistance R at $I_0=0.75$ mA: from dc characteristic curve (MΩ)
1	28	4.0	4
2	25	6.1	6
3	32	2.3	2.5

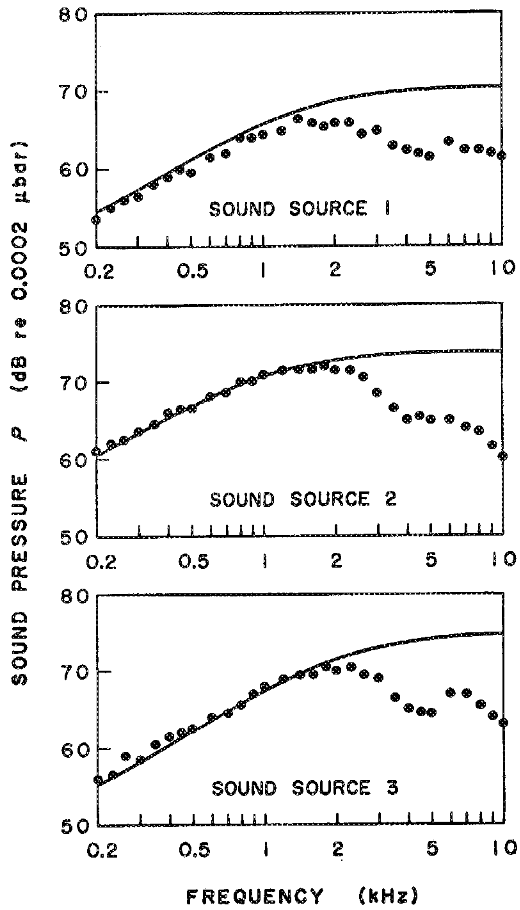

FIG. 9. Frequency responses of sound sources for $I_0=0.75$ mA, $I=0.38$ mA, and $r=50$ cm. ●: experimental; ——: calculated from Eq. 4 and $b=2.2$ cm²/V–sec.

The solid-line calculated curves in Fig. 9 are obtained from Eq. 4, where a certain value of b is used in order that the curves are in the best agreement with the dots for low frequencies. The optimum value of b is 2.2 cm²/V–sec. The curves are in good agreement with the dots up to 1 or 2 kHz. Therefore, b is a constant which is, below 1 or 2 kHz, independent of frequency and common to our three sound sources.

As an addendum, the value 2.2 cm²/V–sec lies in the order of the mobility value of ions in air at atmospheric pressure.[9]

V. CONCLUSIONS

Formulas are obtained for the sound pressure and the directivity of the three sound sources. The experimental results for 0.2–1 kHz are in good agreement with the calculated ones based on those formulas with respect to the following points:

(1) Proportionality between the sound pressure and the ac current.

(2) Directivity.

(3) Decrease in sound pressure caused by connecting a shunting condenser.

(4) Independence of sound pressure from the dc current.

(5) Sound pressure as a function of frequency.

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