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DEVELOPMENT OF AN OMNIDIRECTIONAL CYLINDRICAL SOUND SOURCE WITH A CORONA DISCHARGE TRANSDUCER

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ABSTRACT

The Corona Discharge Transducer (CDT) relies on the electroacoustic actuation of a ionized layer of air through an oscillatory electric field. This device allows sound generation without an intermediate mechanical radiator such as a membrane, making it an almost perfect particle velocity source, with ideal impulse response. Thanks to its membrane-less and construction and its continuous arrangement of uniform linear acoustic antennas, it also permits the development of ideal monopolar sources. This paper presents a cylindrical CDT concept, its design and optimization through numerical models (COMSOL), in a view to the realization of a future experimental prototype. The discussion on the acoustic performance obtained on the models will lead to concluding remarks on its applicability to acoustic metrology.

Keywords: *Plasma physics, corona discharge, directional loudspeakers*

1. INTRODUCTION

In their vast majority, loudspeakers rely on the acoustic radiation of a mechanical component (circular or rectangular diaphragm) or through an acoustical radiator (horn), actuated by an electromechanical driver, most often electrodynamic (although electrostatic, piezoelectric, or pneumatic transducers also exist) [1]. Therefore, the whole electro-acoustic transduction cannot happen without an intermediate, likely to degrade the response to transients (due to the inertia of the membrane), thus yielding audible phase distortions [2].

Besides their limitations in the time domain, loudspeakers relying on mechanical membrane do not allow the effective construction of actual omnidirectional sources, unless through the faceting of polyhedrons, such as dodecahedrons used in room acoustic measurements [3]. These sound sources present directivity pattern close to ideal pulsating spheres at low frequencies (as long as the wavelength remain much larger than the polyhedron dimensions [4]), but become nonetheless directive at higher frequencies.

The development of electroacoustic transducers relying on the Corona Discharge mechanism has been reported back to the 1970's, but the 2000's have seen a surge of interest with the work of Béquin et al with mathematical models [5, 6] allowing their design in different configurations ("point-to-grid", "wire-to-grid", etc.). More recently, a planar loudspeaker relying on a "wire-to-grid" Corona Discharge configuration has been developed by Sergeev et al [7, 8] for applications to active noise control, but also as an "ideal" source of sound (transparent, massless, resonant-free, ideal flow velocity source...).

One interesting property of this device is the combination of two colocated sound sources. A first monopolar source results from the heat release around the ultra-thin electrode (designated "corona electrode") responsible for the ionization of the surrounding medium. The second dipolar source is linked to the electrostatic force responsible of the bulk acceleration/decelaration of positive ions and their consecutive non-elastic collisions with the surrounding (neutral) fluid medium in the "drift region" between the corona electrode and a grounded coarsely perforated metallic electrode (designate "collector electrode").

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In short, the two processes are responsible of the simultaneous generation of two flow velocities, one symmetric and the other anti-symmetric with respect to the median plane of the transducer. It has also been shown that the ratio between the two flow velocity sources was of the order 1:5 (the dipole source being about 5 times stronger than the monopole source), depending on the transducer geometry.

While constructing an ideal spherical source with a corona discharge transducer represents an obvious challenge with the "wire-to-grid" configuration, the cylindrical geometry is much more straightforward to design, and should allow validating the concept of an ideally omnidirectionnal sound source. This paper aims at presenting the development of a cylindrical loudspeaker based on the corona discharge principle with a wire-to-grid configuration, allowing achieving an omnidirectionnal source in the plane perpendicular to its axis of symmetry. In a first section, the principle of the corona discharge and its application to electroacoustic transducers will be shortly reminded, followed by the description of a very simple numerical model on COMSOL Multiphysics, allowing its further design. Finally, preliminary simulation results will be presented, justifying the timeliness of the proposed design, and paving the way to future experimental validations.

2. THE CORONA-DISCHARGE ELECTROACOUSTIC TRANSDUCER

2.1 Reminder of the principle in a "wire-to-grid" configuration

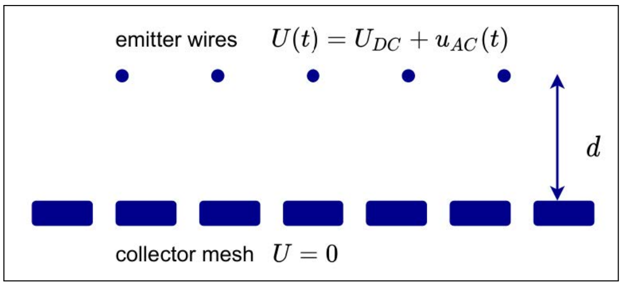

Figure 1. Sketch representing a cut view of the electrode pair: corona electrode (emitter wires)/collector electrode (grounded perforated grid)

Corona discharge loudspeakers allow for sound generation due to the ionization of molecules in the surrounding fluid, moved by an intense oscillating electric field. In the "wire-to-grid" configuration, the transducer is constituted by a pair of electrodes (forming two parallel planes, as illustrated in the sketch of Fig. 1): the first one is a perforated metallic grid connected to the ground, and is designated the "collector electrode"; the second one, designated "corona electrode", is made of an ultra thin wire (diameter of the order of 100 μm), arranged in a pattern of parallel lines along a same plane parallel and distant of d to the collector plane, put at a sufficiently high voltage so as to trigger the extraction of electrons from surrounding molecules. The breakdown voltage, above which ionization is possible, is designated U_0 and is of the order of a few kV.

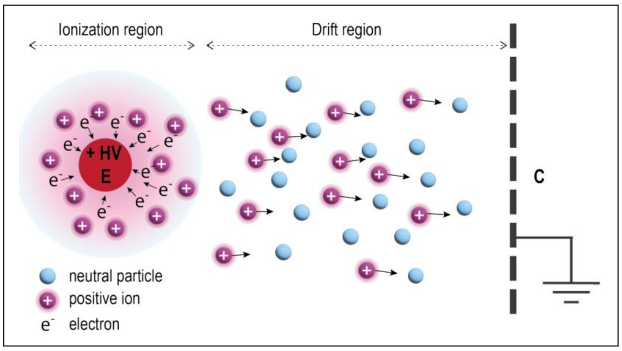

Figure 2. Corona discharge principle

When applying an offset voltage U_{DC} higher than U_0, positive ions are accelerated inside the ionization region towards the collector electrode. They then collide with the neutral particles present in the drift region, which are then moved, giving rise to an "ionic wind" (constant flow).

If an alternating voltage $u_{ac}(t)$, of the order of 1 kV, is superimposed to U_{DC} (while total voltage $U_{DC} + u_{ac}$ still remains higher than the breakdown voltage, as well as not exceeding a value above which arcing may occur), the transducer generates acceleration/deceleration of the surrounding fluid layers, responsible for sound generation.

The preceding studies show that this corona discharge transducer configuration could be modelled as the combination of two volumic sound sources, one monopolar "heat" source H (due to the heat release at the corona electrodes), and another dipolar "force" source F (relative to the electrostatic force moving the surrounding fluid back and forth).

An extremely simple electroacoustic model can be deduced from the coupling equations between the plasma generation and actuation, and the generated sound field. Indeed, it has been shown that the offset voltage U_{DC} can be linked to the current I flowing through the corona wire according to the Townsend formula:

$$I = CU_{DC}(U_{DC} - U_0) \tag{1}$$

where C is a constant that depends on the transducer geometry, and that can be experimentally determined. It is then possible to express the two sources H and F as a function of the voltage feeding the transducer [7, 8]:

$$\begin{aligned} H &= C(3U_{DC}^2 - U_{DC}U_0)u_{ac} \text{ [W]} \\ F &= \frac{C.d}{\mu_i}(2U_{DC} - U_0)u_{ac} \text{ [N]} \end{aligned} \tag{2}$$

where μ_i designates ions mobility, and d is the distance between the two electrodes (or the plasma thickness).

Equation (1) can then be used to express the ”Heat Source” power density (in W/m^3), and the ”Dipolar Domain Source” force density (in N/m^3), by dividing these two expressions by the plasma volume ($S.d$, where S is the transducer effective area) in the COMSOL model.

2.2 Case of a cylindrical ”wire-to-grid” configuration

In this study, we investigate a alternative geometry of the corona discharge electroacoustic transducer, where the collector electrode is composed of a cylindrical perforated metallic grid (alternatively, composed of cylindrical rods arranged to form a cylinder shape around the symmetry axis), of height h, bounded by two rigid plates on both sides, over which an ultrathin wire can be arranged to form a network of parallel wires distant of e from each others, and distant of d from the collector. Fig. 3 illustrates the proposed configuration.

It seems quite obvious that, in this configuration, the dipolar force source is cancelled by the axisymmetry of the transducer, giving rise to the only monopolar heat source. It should then behave as an ideal omnidirectional sound source in the horizontal plane, or in azimuth (according to the convention of Fig. 3, the symmetry axis being along the vertical). Note that the transducer directivity in elevation (with respect to the z axis) should correspond to the one of a finite radiating cylinder, according to Williams et al [9].

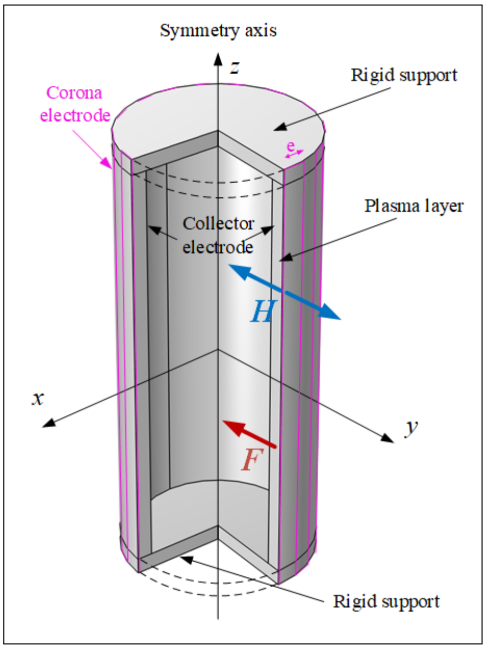

Figure 3. Cylindrical plasma loudspeaker geometry

3. NUMERICAL MODEL

3.1 Description of the COMSOL model

A COMSOL Multiphysics model has been developped to verify the acoustic properties of the transducer elaborated before. The model uses the only *Pressure Acoustics, Frequency Domain* (acpr). We have chosen to develop a full 3D model of the transducer in a view to assess further configurations in the future, not only the axisymmetric one (for which the only 2D Axisymmetric Space Dimension would have been sufficient). Especially, we will be interested in investigating a dipolar transducer configuration in the future (not presented here). However, in order to save computational time, we assumed the horizontal plane xOy and the vertical plane xOz are planes of symmetry, thus limiting the 3D model to a quadrant of a sphere.

We start by modeling the geometry in the xOz plane, and generate the 3D model by semi-revolution along axis z. In this plane, we draw the propagating domain as a quadrant of a circle of radius $D = 1$m, surrounded by a Perfectly Matched Layer of depth $D/5 = 0.2$ m. The cylindrical loudspeaker is represented by a rectangular layer of height $h/2$ and width d, shifted by distance R from the axis of symmetry z. This plasma layer is capped by a rigid frame of width $R + d$ and height t, which is substracted from the propagation domain, the remaining boundaries being set as "Sound Hard Boundary".

Here, we will consider the plasma layer model presented by Sergeev et al [7, 8], namely considering the plasma layer of volume $V = \pi(d^2 + 2d.R).h$ as an homogenous air medium embedding one "Heat Source" domain (power density $Q_{heat} = H/V$, to which we should precise the isobar heat capacity C_p and adiabatic coefficient γ), and a "Dipolar Domain Source" (power density $q_d = -F/V$ along the xOy plane, the - sign indicating that the corona electrode is located on the exterior side of the cylinder, although this component should have no effect in this geometry). Fig. 4 illustrates the chosen model geometry in 2D.

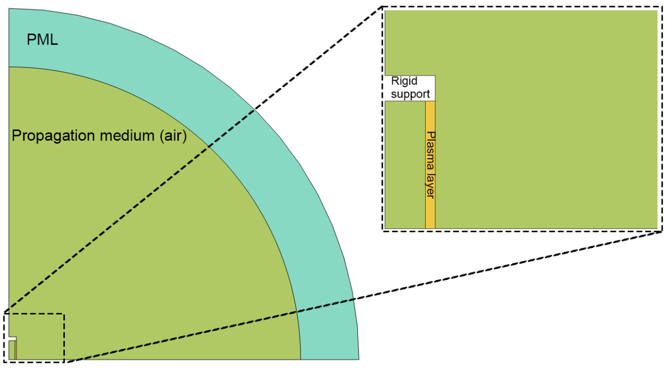

Figure 4. Intermediate 2D COMSOL model

The parameters used to design the COMSOL model are given in Tab. 1. Note that the dimensions have been chosen to meet the ones of a planar version of the corona discharge loudspeaker, assuming the electroacoustic properties (especially coefficient C) is only dependant on the transducer dimensions (inter-electrode distance d, corona wire diameter, and overall corona wire length, linked to the effective area of the transducer S). With these assumptions, there is no need to build a prototype to evaluate the electroacoustic model parameters, which simplifies the modeling and design phase. The following parameters mostly refer to a former design reported in [10].

Table 1. Model parameters

Parameter	Symbol	Value	Unit
Medium (air) properties			
Density	ρ_0	1.23	kg.m^{-3}
Speed of sound	c	343	m.s^{-1}
Isobar heat capacity	C_P	1015	J.kg^{-1}K^{-1}
Adiabatic coefficient	γ	1.4	-
Ions mobility	μ_i	1.1.10^{-4}	m^{2}V^{-1}s^{-1}
Transducer dimensions			
Plasma thickness	d	5	mm
Wires spacing	e	10	mm
Height	h	13	cm
Internal radius	R	2.5	cm
Support thickness	t	13	mm
Electrical characteristics			
DC voltage	U_{DC}	8	kV
Breakdown voltage	U_0	6.16	kV
Current/voltage constant	C	1.8 10^{-11}	A V^{-2}

Last, the 2D model drawn in the xOz *Work Plane* is extruded in semi-revolution to obtain the 3D model of Fig. 5.

The simulations are performed in the frequency domain, for ISO frequencies split in 1/24$^{\text{th}}$ octave spanning the [125 Hz - 2000 Hz] range. The tetrahedral meshing was limited to one sixth of a wavelength at 2000 Hz. Presented results will limit to octave bands central frequencies.

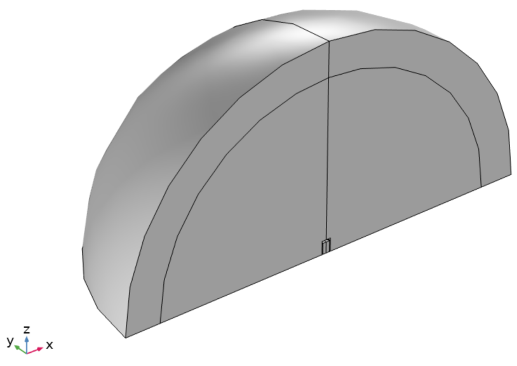

Figure 5. Full 3D COMSOL model

3.2 Simulations results

We present the directivities of the cylindrical plasma loudspeaker in azimuth (Fig. 6) and elevation (Fig. 7). Regarding the directivity in azimuth, it is obvious that the transducer is perfectly omnidirectionnal in the xOy plane, which justifies the chosen geometry. Moreover, the achieved directivities in elevation confirm that the sound radiation conforms to the one of a finite pulsating cylinder, as described by Williams et al. [9].

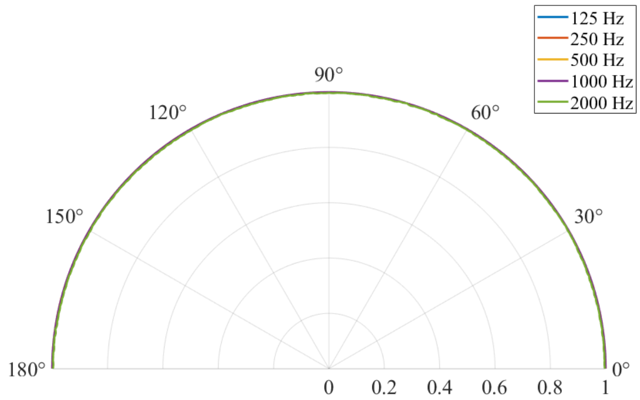

Figure 6. Directivity in azimuth

Moreover, the acoustic pressure along the Ox axis, illustrated on Fig. 8 corresponds to the sound radion model of a finite cylinder reported in [9].

Last, the radiation impedance of the cylindrical plasma transducer is obtained by first integrating the

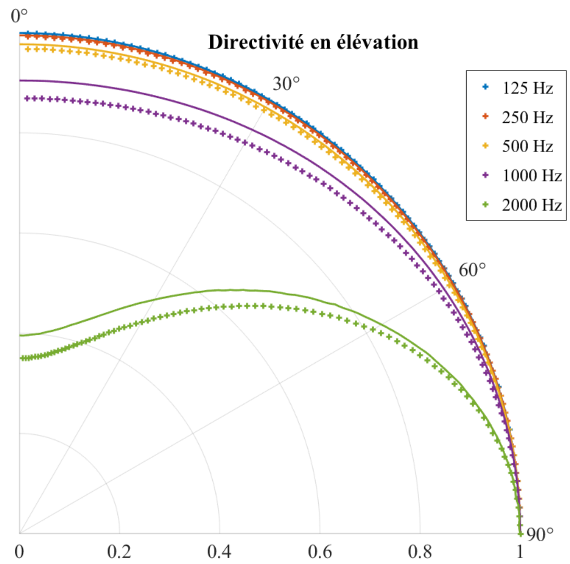

Figure 7. Directivity in elevation (lines: COMSOL simulations; + markers: theoretical results after Williams et al [9])

sound pressure and the normal velocity over the plasma outter boundary to derive the net pressure force and flow velocity, and then expressing their ratio normalized by $Z_c = \rho_0.c_0$. The normalized radiation impedance is illustrated on Figure 9.

4. CONCLUSIONS AND PERSPECTIVES

We have been able to verify, with the COMSOL model, the hypothesis after which a corona discharge loudspeaker following a cylindrical geometry behaves as a monopolar sound source in a first approximation (ie. considering the cylindrical plasma layer generates the same amount of monopolar / dipolar sound sources than a plane geometry of same dimensions), the dipolar force source being cancelled by symmetries. The main drawback is the lower sound pressure amplitude radiated by the monopolar source compared to the dipolar (about 5 times less), explaining the low acoustic efficiency of the transducer. Another drawback (also visible on other geometries) is its high-pass filter behaviour, linked to its ideal flow velocity source characteristics, associated to the radiation impedance of a pulsating cylinder. Last, the finite dimension of the transducer yields a directivity in elevation similar to the one of a finite pulsating cylinder of radius R and

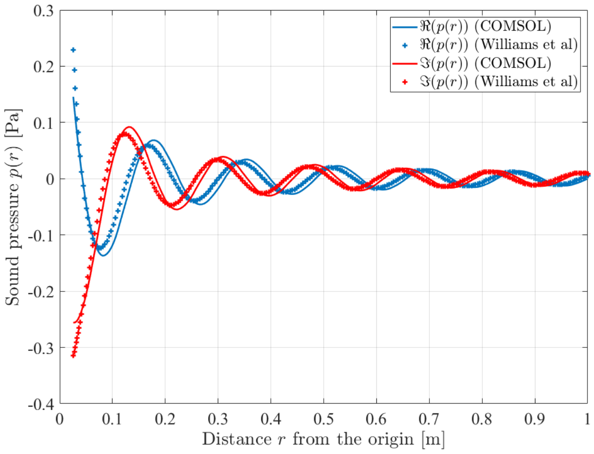

Figure 8. Acoustic pressure along Ox, at 2000 Hz: lines: COMSOL simulation results (blue: real part, red: imaginary part); markers: theoretical results after Williams et al [9] (blue: real part, red: imaginary part)

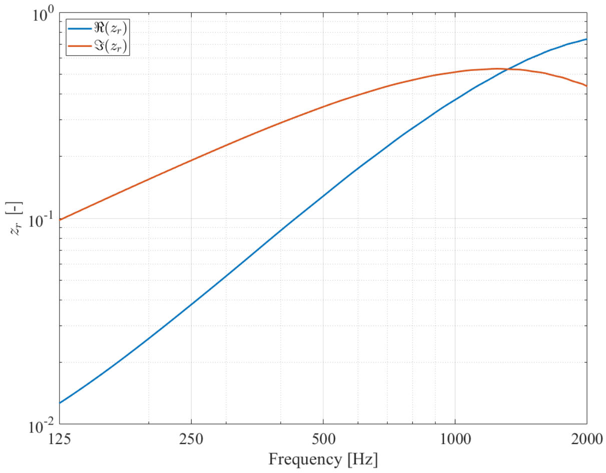

Figure 9. Normalized radiation impedance derived with the COMSOL model (blue: radiation resistance; red: radiation reactance)

height h [9].

The next step will consist in constructing a prototype based on the proposed geometry, and the assessment of its acoustic radiation in an anechoic facility. Moreover, we anticipate to test some alternative transducer configurations, for example in a "dipolar-only" version, where the transducer would be made of two half-cylinders, each fed with its own voltage amplifier, one with voltage $u_{ac,1}$ and the other with out of phase voltage $u_{ac,2} = -u_{ac,1}$. These planned experiments should confirm the results of this preliminary simulation study and open the way to new controllable directionnal sound sources, allowing changing the directivity from omnidirectionnal to bidirectionnal (two-sided), and beyond, multipolar by further partitions of the cylinder.

The applications of such an omnidirectionnal source are manifold: it first allows verifying sound radiation models used for the design of ideal sound sources, such as pulsating spheres and cylinders, which are accessible to experiments only through the simplification of their geometry as polyhedrons. Besides this theoretical interest, having effective omnidirectionnal sound sources could be an important asset for acoustic metrology, more specifically for room acoustics measurements, as a substitute to state-of-the-art dodecahedrons.

5. ACKNOWLEDGMENTS

The authors would like to honor the memory of Tirui Wang, a student in Micro-Engineering at EPFL, having collaborated to the development of the cylindrical plasma loudspeaker, who tragically passed away in China, his home country, on February 14, 2025.

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