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Acoustic particle displacement resonator

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ABSTRACT

A simple device consisting of a waveguide and two loudspeakers is proposed for generation of low-frequency standing acoustic field with high amplitude of acoustic velocity and particle displacement, which is primarily intended to be used for stabilization of electric discharges in acoustic field. A coupled model of loudspeakers and nonlinear wave equation including waveguide radius variability, thermoviscous attenuation in boundary layer and minor losses is developed. The results of the conducted experiments validate the model revealing that the minor losses and acoustically generated turbulence in the boundary layer represent an important means of acoustic energy dissipation in this and similar applications.

1. Introduction

In recent years, some non-conventional applications utilizing high-amplitude acoustic fields have begun to develop; acoustic compressors, mixers, thermoacoustic engines or refrigerators can serve as an example. Another example is stabilization of electric discharge in acoustic pressure node of a high-amplitude standing wave, see e.g. [1,2], which finds its application in plasma-chemical reactors increasing the efficiency of the processes leading to the destruction of toxic pollutants, decomposition of volatile organic compounds, etc. It has been found in work [2] that acoustic field with high amplitude of particle displacement plays a key role in these processes so it is desirable to find an effective way of its generation. As the acoustic displacement amplitude is for given acoustic velocity amplitude inversely proportional to frequency, it is necessary, in case of standing waves, to pay an attention to reasonable dimensions of the used machinery.

For this reason (and we are convinced that there would also be other applications) a simple device has been proposed for generation of standing acoustic field with high amplitudes of acoustic particle displacement, which is the subject of this article. Section 2 describes its construction and experimental techniques used, Section 3 deals with a theoretical model which is needed in order to understand the underlying physics. Section 4 presents the obtained results and comparison of experimental data with the model predictions, Section 5 then concludes the article.

2. Experimental setup

2.1. Low-frequency acoustic resonator

The proposed device allowing generation of acoustic field with high amplitude of acoustic velocity and displacement is schematically depicted in Fig. 1. It consists of two electrodynamic transducers (loudspeakers) B&C 6MD38-8 (power handling 240 W), enclosed in small loudspeaker-boxes, connected in antiphase in series, which drive acoustic field in a waveguide (plexiglass tube with inner radius $r_1 = 12$ mm, length $2 \times l_1 = 300$ mm and thickness 2 mm) through conical segments (made from plastic funnels, small inner radius $r_1 = 12$ mm, large inner radius $r_2 = 75$ mm, length $l_2 = 60$ mm) and short segments with inner radius r_2 and length $l_3 = 40$ mm. Due to the antiphase driving of the loudspeakers, the primary acoustic field (the first harmonics) has node of acoustic pressure and anti-node of acoustic velocity and particle displacement at the centre of the waveguide. The loudspeakers are driven by a harmonic signal which is amplified using power amplifier Akiyama AMD400.

2.2. Measurements

Electrical and acoustical measurements on the proposed device were conducted as follows.

Input electrical impedance was measured using a home-made program written in LabView which controls a sine-wave generator (Agilent U2761A) and AC voltmeter and ammeter (Agilent U2741A). The generated signals were amplified by a power

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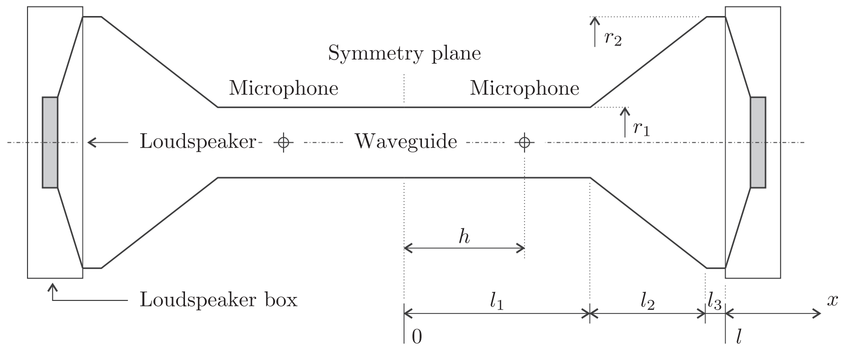

Fig. 1. Arrangement of the device.

amplifier, the measurements were conducted at constant voltage amplitude. The same equipment was used for measurement of impedance characteristics of the loudspeakers in vacuum in order to determine their parameters, see e.g. [3], using the nonlinear least-squares fit.

Acoustic velocity and particle displacement at the centre of the device were determined using the two-microphone method, see e.g. [4]. Two 1/8" microphones (G.R.A.S. Type 40DP) were placed symmetrically along the centre in the waveguide wall separated by the distance of $2 \times h = 160$ mm, measuring acoustic pressures $p'_A(t)$ and $p'_B(t)$. If the microphones separation $2 \times h \ll \lambda$, where λ is the wavelength, acoustic velocity v between the microphones can be calculated using the linearised Euler's equation as

$$v(t) = \frac{1}{\rho_0} \int \frac{p'_B(t) - p'_A(t)}{2h} \mathrm{d}t, \tag{1}$$

where ρ_0 is the ambient fluid density. Acoustic particle displacement $\xi(t)$ can be then calculated as

$$\xi(t) = \int v(t) \mathrm{d}t. \tag{2}$$

The microphone signals were amplified (G.R.A.S. Type 26AC Preamplifiers + G.R.A.S. Type 12AB Microphone Power Module) and digitized using DAQ card (National Instruments PCI-6251) controlled by a LabView-written program; the integrals in Eqs. (1) and (2) were calculated using the FFT method implemented in Matlab.

3. Theoretical model

3.1. Model equation for acoustic field in a waveguide

High-amplitude acoustic field inside a variable-cross-section waveguide can be described using a set of two quasi-one-dimensional equations

$$\frac{\partial p'}{\partial x} = -\rho_0 \frac{\partial v}{\partial t} - \frac{p'}{c_0^2}\frac{\partial v}{\partial t} + \frac{v}{c_0^2}\frac{\partial p'}{\partial t} + \frac{2}{r}\frac{\mathrm{d}r}{\mathrm{d}x}\rho_0 v^2 + \frac{\rho_0 \delta_v}{c_0^2}\frac{\partial^2 v}{\partial t^2}, \tag{3a}$$

$$\frac{\partial v}{\partial x} - \frac{2\varepsilon}{r^2}\frac{\partial^{1/2}(rv)}{\partial t^{-1/2}\partial x} = -\frac{1}{\rho_0 c_0^2}\frac{\partial p'}{\partial t} - \frac{2}{r}\frac{\mathrm{d}r}{\mathrm{d}x} v + \frac{\gamma}{2\rho_0^2 c_0^4}\frac{\partial p'2}{\partial t} + \frac{1}{2c_0^2}\frac{\partial v^2}{\partial t} + \frac{\delta_t}{\rho_0 c_0^4}\frac{\partial^2 p'}{\partial t^2}, \tag{3b}$$

where $p' = p - p_0$ is the acoustic pressure, p is the total pressure, p_0 is the ambient pressure, v is the acoustic velocity, t is the time, x is the spatial coordinate along the waveguide, $r = r(x)$ is its radius, c_0 is the small-signal speed of sound, γ is the adiabatic exponent, $\delta_v = (\zeta + 4\eta/3)/\rho_0$ is the diffusivity of sound due to viscosity, where η, ζ are the coefficients of shear and bulk viscosity, respectively, $\delta_t = \kappa(1/c_V - 1/c_p)/\rho_0$ is the diffusivity of sound due to thermal conduction, where κ is the coefficient of thermal conduction and c_p, c_V are the specific heats at constant pressure and volume, respectively. Further, $\varepsilon = \sqrt{\nu_0}[1 + (\gamma - 1)/\sqrt{Pr}]$, where $\nu_0 = \eta/\rho_0$ is the kinematic viscosity and $Pr = \eta c_p/\kappa$ is the Prandtl number. The term with coefficient ε describes the acoustic energy dissipation in the boundary layer; additional losses due to acoustically generated turbulence, which appear to play an important role in this case, are incorporated into the coefficient ε in a straightforward way, see Appendix A and [5].

Eq. (3) are derived in the second approximation, they account for waveguide cross-section spatial variability, nonlinearity, thermoviscous volume attenuation and thermoviscous attenuation in the boundary layer. The derivation is briefly sketched in Appendix A. Use of Eq. (3) in this case is more advantageous than employing the model equations used e.g. in works [6,7], as Eq. (3) are formulated using the primary acoustic variables p', v and it is thus simple and straightforward to couple them to a model of an electro-acoustic transducer or to a model of the minor losses.

As we are further focused on periodic steady-state acoustic fields, the acoustic quantities are represented as

$$q(x,t) = \frac{1}{2}\sum_{n=-N}^{N} \hat{q}_n(x) \mathrm{e}^{\mathrm{i}n\omega t}, \tag{4}$$

where $q(x,t)$ stands for $p'(x,t)$, $v(x,t)$ and $\hat{q}_n(x)$ represents individual (complex) harmonics. Further, ω is the driving frequency, N is the number of harmonics taken into account and $\hat{q}_{-n}(x) = \hat{q}_n^*(x)$, where the asterisk denotes the complex conjugate, because of the fact that physical quantities are represented by real functions. Substituting expansion (4) into Eq. (3) results in a set of $2N + 1$ ordinary differential equations (ODEs) for phasors $\hat{p}'_0, \ldots, \hat{p}'_N$, $\hat{v}_1, \ldots, \hat{v}_N$. The ODEs were integrated numerically using the adaptive-step-size eight-order Runge–Kutta method, see e.g. [8].

3.2. Model of the loudspeakers

The loudspeakers situated at the ends of the waveguide, see Fig. 1, are modelled using lumped-element circuits, see e.g. [3], the corresponding equations represent the boundary conditions for Eq. (3) at $x = -l$ (the left loudspeaker) and $x = l$ (the right loudspeaker) and have the form

$$\left[Z_e Z'_m + (Bl_{vc})^2\right]\hat{v}_n + Z_e S_d \hat{p}'_n - Bl_{vc}\hat{u}_n^L = 0 \quad \text{for} \quad x = -l, \tag{5a}$$

$$-\left[Z_e Z'_m + (Bl_{vc})^2\right]\hat{v}_n + Z_e S_d \hat{p}'_n - Bl_{vc}\hat{u}_n^R = 0 \quad \text{for} \quad x = l, \tag{5b}$$

where $Z_e = R_e + \mathrm{i}n\omega L_e$ is the electrical impedance of the loudspeaker voice coil, R_e is the electrical resistance and L_e is the electrical inductance; $Z'_m = Z_m + S_d^2/\mathrm{i}n\omega C_a$, where $Z_m = R_m + \mathrm{i}n\omega M + 1/\mathrm{i}n\omega C_m$ is the loudspeaker mechanical impedance, R_m is