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On Certain Practical Issues Relating to Construction of the In-duct Single Mode Synthesizer

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It is convenient to have a device and a method of generating single cut-on modes in cylindrical hard-walled waveguides or at least in laboratory models of such systems. This allows to examine, among other things, properties of various active and/or passive elements inserted in a cylindrical duct by testing them in conditions when the incident (input) wave comprises only one cut-on mode and determining the reflection and transmission coefficients for single selected incident modes. As it has been already demonstrated by the present authors, it is possible to generate single cut-on modes in a circular duct using a small (although increasing with mode order) number of acoustic monopoles arranged properly on a duct cross-section and driven with appropriate acoustic volume amplitudes and phases. Laboratory models of such sources are proposed in this paper and results of tests verifying their directional properties are presented. The other technical issue relating to practical utilization of the proposed method is the possible error introduced by the apparatus used for scanning the acoustic field inside the duct model. It is shown that insertion of the measuring probe changes the total energy radiated into the free space only by a fraction of a decibel.

Keywords: circular hard-walled duct, modal structure, cut-on mode, circular duct modeling.

1. Introduction

In many problems encountered in the environment protection against noise pollution, prediction of sound level produced by ducted sound sources such as, for example, rotors, fans, compression chambers, etc., is of great interest to manufactures/designers of heating, ventilation, and air-conditioning (HVAC) systems. The same importance may be attributed to the space distribution of noise radiated from outlets of automotive engines and aircraft turbines mounted inside cylindrical housings. This is due to the fact that ducts most frequently used in practice are hard-walled structures and so transmit the acoustic energy/power with great efficiency causing harmful environmental pollution.

The contemporary tend in designing the above-mentioned devices is to have predicted the sound field produced by them at the design stage and so substantial effort has been put by many research groups into developing new techniques to complete this task. As it will be presented below, many of these techniques are based on representing the field produced by a complex source with the use of a certain distribution of point sources located inside the duct. Therefore, it is of importance to find a proper realization of an idealized acoustic point source known as the acoustic monopole which could be mounted inside the duct, to produce the sound field strong enough to carry on measurements, and demonstrate the basic property of the monopole, i.e. – omnidirectional radiation directivity pattern, with sufficient accuracy. In the present paper, realization of a monopole source as an outlet of a thin tube is proposed and validated by measurements.

Once such model of elementary acoustic source is available and used to reproduce real-life sources existing in a duct, another problem arises in experimental practice. To examine the existing spatial distribution of the sound pressure and its modal structure, measurements have to be taken on the duct cross-section. This will inevitable lead to some discrepancy between theoretical predictions and experimental data caused by the finite size of a microphone, which in this case cannot be mounted flush on the duct wall but its positioning in consecutive measurements must cover the whole duct cross-section.

In the following, we restrict ourselves to analysis of the effect of microphone placement within the waveguide on the acoustic power radiated outside which is an indirect measure of disturbance of the field inside the waveguide caused by its presence.

Theoretically, derivation of a considered acoustic field at a given source/sources operation can be achieved by solving the inhomogeneous wave equation with the right-hand side describing sound sources. However, in practice, this solution is known only for sources far less complicated than fans or rotors, not to mention automotive or jet engines. Until now, solutions of the wave equation have been obtained for some simple sources, such as the acoustic monopole, dipole, quadrupole, etc. The solution for an acoustic monopole located inside the duct, known as the Green's function of the Helmholtz wave equation (called also the in-duct Green's function), can be applied, due to the principle of superposition, to sets of such sources forming more complex structures. The Green's function technique is widely applied to solving numerous in-duct problems (Rienstra, Tesler, 2005; Rienstra, Hirschberg, 2007; Bravo, Maury, 2008; Snakowska *et al.*, 2014).

Some other methods are based on solving the so-called inverse problem, which means reconstruction of the spatial distribution of ducted sources from measurement data taken in the considered field (Lavrientjev *et al.*, 1995; Bravo, Maury, 2010; Kim, Nelson, 2004; Gorazd *et al.*, 2014a). Most of the methods of in-duct sources reconstruction are based on modes decomposition, i.e. reconstruction of modal content of the resulting sound field inside the duct comprising a sum of modes, each of them representing the particular solution of the Helmholtz wave equation. Out of these solutions, determined by two indices representing their circumferential and radial orders, only the so-called propagating modes are taken into account (Rienstra, Hirschberg, 2007). And so, the equivalent source method (Bravo, Maury, 2008; 2010; Lowis, Joseph, 2006) consists in spatial discretization of the cross-section source area into a number of monopoles and application of the cylindrical hard-wall duct Green's function (Bravo, Maury, 2008).

Another way to overcome difficulties in obtaining detailed sound sources characteristics is to introduce some additional assumptions allowing to predict the acoustic field propagated in the duct and radiated outside. Determination of the in-duct acoustic field in case of multimodal wave excitation is only possible if the sound source distribution function or complex amplitudes of the consecutive modes are known *a priori*. Thus, these additional assumptions refer to a specific distribution of mode amplitudes and are therefore called the mode amplitude weighting functions (Snakowska, 1993; Joseph, Morfey, 1999; Joseph *et al.*, 2002; Sinayoko *et al.*, 2010). Frequently applied are the ones calculated for a set of incoherent monopoles/axial dipoles uniformly distributed over the duct cross-section (Joseph, Morfey, 1999; Joseph *et al.*, 2002; Sinayoko *et al.*, 2010).

In numerous practical problems dealt with in the acoustics of waveguides, especially in modeling noise generation, propagation, and radiation in systems constructed of or comprising tube-shaped components, actual sources are sometimes idealized by means of systems of acoustic monopoles distributed inside ducts (Kim, Nelson, 2004; Bravo, Maury, 2008; 2010). However, any theoretical solutions should be verified experimentally. For this reason it is the matter of primary importance to examine the feasibility of the task of constructing an actual sound source with properties as close as possible to those characterizing an omnidirectional "mathematical" point source. Specific spatial systems of such sources, having in particular a form of planar matrices with positions, amplitudes, and phases determined on the grounds of an analysis carried out with the use of the Green's function formalism and the modal decomposition method, could be used to generate single higher wave modes (Snakowska *et al.*, 2014). Such "mode synthesizers" could prove useful in testing different theories based on modal approach (Snakowska, 1995; Akoum, Ville, 1998; Sittel, Ville, 2006; Snakowska, Jurkiewicz, 2010; Gorazd *et al.*, 2014b).

In the study reported in this paper, the proposed model of a point monopole acoustic source is the outlet of a thin tube, connected with a driver producing the required harmonic acoustic volume output. A number of different geometrical modifications of such output were examined within the frequency range 400–10000 Hz, in which other analyses of acoustic field of the cylindrical hard-walled waveguide were also carried out by the present authors.

On the other hand, when examining distribution of acoustic field within a duct by means of microphone placed inside, introduction of a measuring instrument characterized with finite dimensions is connected with some field disturbance. The issue of the related error is examined quantitatively in Sec. 4 of this paper.

2. Point sources distributed inside the duct. The planar mode synthesizer

From what was said above it is obvious that the model of monopole sources distributed inside the duct is frequently applied to solve various in-duct problems. Theoretically, the solution of the problem of a monopole source operating in a duct is well known, as for time-harmonic excitation its spatial part represents the solution of an inhomogeneous Helmholtz equation with the right-hand side in the form of Dirac delta function $\delta(\mathbf{r}-\mathbf{r}')$, where $\mathbf{r}'$ represents the position of a point source with the unit volume output $\int\limits_{S_0} \mathbf{v}\cdot \mathrm{d}\mathbf{s}$, where $\mathbf{v}$ denotes the acoustical velocity and S_0 is any surface encompassing the source,

$$(\Delta + k^2)p(\mathbf{r}) = -4\pi\delta(\mathbf{r}-\mathbf{r}'), \tag{1}$$

that is, the Green's function $G(\mathbf{r},\mathbf{r}')$ of the operator $\widehat{L} = \Delta + k^2$ (Rienstra, Hirschberg, 2007). Introducing the appropriate boundary condition corresponding to pressure-release surface (Dirichlet), reflecting surface (Neumann), or impedance surface (Robin) on the duct wall of radius a, the solution, known as the Green's function of a cylindrical duct takes the form

$$G(\rho \le a, \varphi, z, \rho', \varphi', z') = \sum_{m=-\infty}^{\infty}\sum_{n=0}^{\infty} \frac{i\psi_{mn}(\rho,\varphi)\psi^*_{m'n'}(\rho',\varphi')}{(-2\gamma_{mn})} e^{-(z-z')\gamma_{mn}}, \tag{2}$$

where $\psi_{mn}(\rho,\varphi) = \Lambda_{mn}^{-1} e^{im\varphi} J_m(\beta_{mn}\rho)$ is the $(m,\, n)$ mode shape function, Λ_{mn} is the modal normalization constant introduced to satisfy the orthonormality of the mode shape function on the duct cross-section $\langle \psi_{mn} \mid \psi_{m'n'}\rangle = \delta_{mm'}\delta_{nn'}$ (Watson, 1992), $J_m(\ )$ is the Bessel function of the first kind, and β_{mn} is the radial wave number fulfilling the appropriate boundary condition. In a hard wall duct of radius a, the condition will read $J'_m(\beta_{mn}a) = 0$, compared to $J_m(\beta_{mn}a) = 0$ in a pressure release duct. The radial wave number fulfils the relation $\beta^2_{mn}+\gamma^2_{mn} = k^2$, where γ_{mn} is the axial wave number and k is the wave number in a free-field conditions (Rienstra, Hirschberg, 2007).

For a number N of point sources with complex amplitudes A_i, the acoustic pressure is

$$p(\rho \le a, \varphi, z) = \sum_{i=1}^{N} A_i G_i(\mathbf{r},\ \mathbf{r}'_i). \tag{3}$$

The above formulae may serve modelling a specific "real" source by adjusting spatial distribution of monopole sources and applying the Green's function together with the technique of modal decomposition to calculate the acoustic field. They can also be used to determine analytically appropriate complex amplitudes (module and phases) for each of the point sources to obtain the field composed of only one higher mode, which in turn can be realized by means of a matrix of point sources (Snakowska *et al.*, 2014). However, the transition from theoretical considerations to practical applications as well as comparison of theoretical predictions with experimental results remains nothing but a hypothetical option as long as the physical realization of the mathematical model of a point source is not proposed and verified against experimental data.

In many duct acoustic facilities the acoustic drivers/microphones were mounted flush with the duct wall (Abom, 1989; Akoum, Ville, 1998; Sittel, Ville, 2006). In some experiments carried out in KTH Wallenberg Laboratory aimed at mode decomposition 10 microphones were applied (Abom, 1989) while Jeong *et al.* (2006) proposed the matrix made of 133 sources distributed on 7 rings, comprising 19 drivers each, to obtain the prescribed modal field at high Helmholtz numbers (reduced frequencies) ka. In our work, we focused on providing a some new method of carrying out measurements which would involve much lower financial investments. Based on analysis of possible ways of producing the measurement set-up at low costs, but still fulfilling conditions of scientific research requirements, we have decided to construct a duct facility in which different field configurations would be obtained by means of a planar source synthesizer, i.e. a matrix containing a variable number of "point" sources with properties as close as possible to those characterizing their mathematical prototype.

3. Thin tube outlet as a realization of point source

Finally, in the constructed experimental set-up, the model of a point source was realized as an outlet of a thin steel tube of a length l = 400 mm driven by a loudspeaker. The outer and inner radii of the tube were r_{out} = 6 mm and r_{in} = 5 mm, respectively. The tube was provided with six different types of terminations presented in Figs. 1 and 2. For each of them, the microphone frequency spectrum was registered and compared to spectra of the generated and reference signals. Another way to verify the proposed realization of a point source model consisted in measuring the directivity characteristics in the free-field conditions offered by the AGH large anechoic chamber.

As it has been already mentioned above, it has been decided that the outlet of a thin steel tube will be adopted as a model of idealized concept of the point acoustic volume source (acoustic monopole). The required volume output was provided by a small loudspeaker radiating into a chamber connected with said thin tube via a conical adapter. To ensure or at least

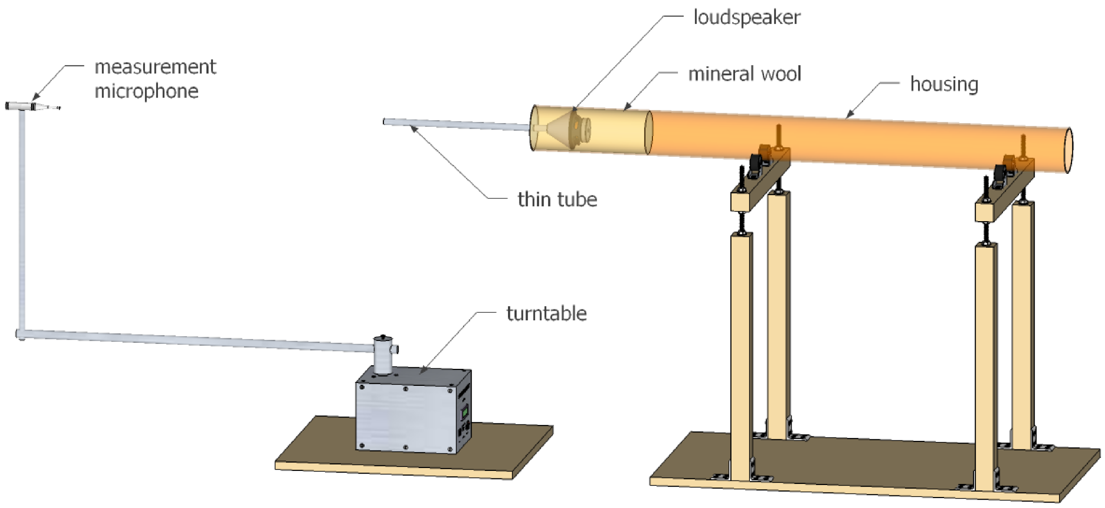


Fig. 1. Measurement setup – a schematic view.

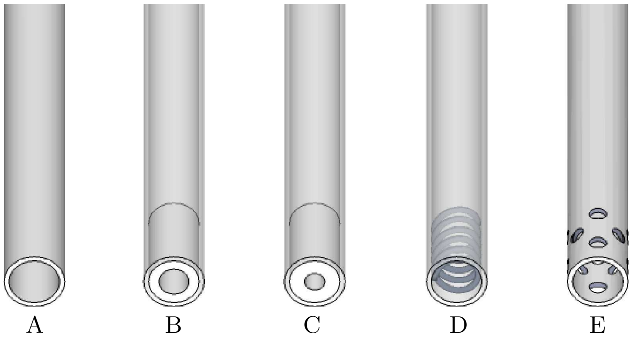


Fig. 2. Configurations of tube tip modeling the acoustic point source.

improve omnidirectionality of the acoustic volume distribution in space and thus also uniformity (spherical nature) of the wave radiated from tube outlet, different modifications of the tube tip were examined. A series of measurements was carried out in free-field conditions to verify suitability of the proposed solutions. Directivity patterns have been determined as well as signal spectra registered for various configurations and modifications of the tube tip.

These experiments have been carried out for the following tube tip configurations shown in Fig. 2:

A – plain tube of length $l = 400$ mm with regular circular outlet $r_{\text{out}} = 6$ mm, $r_{\text{in}} = 5$ mm;

B – tube of the same length tipped with a sleeve of inner radius $r_{\text{in}} = 3$ mm and length $l_1 = 20$ mm mounted inside;

C – tube of the same length tipped with a sleeve of inner radius $r_{\text{in}} = 2$ mm and length $l_1 = 20$ mm mounted inside;

D – tube of the same length with a spiral of inner radius $r_{\text{in}} = 3$ mm and length $l_1 = 20$ mm inserted at outlet;

E – tube of the same length with perforated tip comprising 12 holes with diameter of 3.5 mm each distributed evenly on the final 20-mm long section of the outlet.

Moreover, radiation of sound wave emitted from a tube of the same length 400 mm provided with a perforated sphere surrounding the outlet, as shown in Fig. 3, was also examined with the following variants of such termination:

F1 – tube outlet provided with a perforated sphere (25 holes with a diameter 4.5 mm each evenly distributed over a sphere with radius 39.5 mm);

F2 – tube outlet located centrally in a perforated sphere (same as this used in F1);

F3 – tube outlet located centrally in a perforated sphere (57 holes with a diameter 4.5 mm each evenly distributed over a sphere with radius 39.5 mm).

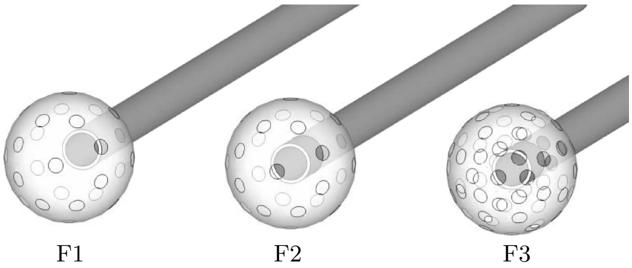


Fig. 3. Various configurations of tube tip terminated with perforated sphere.

Conditions or measurements are described in Subsec. 3.2. At the same time, the reference voltage signal coming directly from loudspeaker terminals was recorded.

3.1. The spectrum

Figure 4 presents spectra of three signals: the generated signal, the reference signal, and the signal recorded by a microphone in the free-field conditions. It become apparent in the course of preliminary tests that linking the source-modeling tube with loudspeaker by means of a funnel- shaped connector (adapter) results in a resonance. In such configuration, the tube behaves as a half-wave resonator, the effect of which can be noticed on the recorded signal plot shown in Fig. 4a. The same figure shows also successive vibration modes calculated according to the formula

$$f_{\text{res}} = \frac{nc}{2(l + \Delta l_1 + \Delta l_2)}, \tag{4}$$

where $n = 1, 2, 3...$ are orders of subsequent resonance frequencies, c is the speed of sound, $l = 400$ mm is the tube length, and Δl_1 and Δl_2 are the adjusted open end correction coefficients (OECC) (Levine, Schwinger, 1948; Dang *et al.*, 1998; Snakowska *et al.*, 2011). It is obvious that the geometry of an open end and the radiation conditions (free field, confined regions) affect the acoustic phenomena (reflection, radiation) and so, the OECC. Moreover, these coefficients depend on the reduced frequency ka and are usually given in the limit of ka approaching zero. According to our knowledge, there is no analytical, computed, or experimental value of the OECC for a horn-like tube end operating in confined region matching the conditions met in our measurement set-up (the funnel facing the loudspeaker membrane, cf. Fig. 1) and so its evaluation can be only approximate, what in turn affects the calculated resonance frequencies. Thus, calculating the resonant frequency we applied two different OECC, resulting in two different length corrections: $\Delta l_1 = 0.6133a$, appropriate for the end of an unflanged tube of radius a radiating in the free field conditions, and Δl_2 – adjusted, based on values reported in literature for a funnel operating at the other end of the tube which can be approximated by an acoustic horn. The values of OECC for a horn-shaped open end operating in the free field conditions found in the literature vary from 0.46 (Peters *et al.*, 1993) to previously suggested value 0.6133 and are to be multiplied by the horn radius rather than the pipe radius (Peters *et al.*, 1993). Moreover, research on OECC in the confined region reported by Dang *et al.* (1998) indicate that the measured and computed transfer functions for a path with a side branch (cf. Fig. 4 therein) are better consistent for lower frequencies (below 3.5 kHz) and the discrepancy raises with the frequency, the fact which is also observed in our results. In the same paper, the authors consider OECC for different realizations of side branches within an acoustic tube. They obtain the OECC varying in the range 0.76–0.88 which means that the values derived for confined regions exceed, in general, the ones obtained for radiation in the free field. Basing on the above-presented results, in our calculations of the consecutive resonant frequencies we applied the OECC equal to 0.8 as matching the conditions of the experimental set-up. It follows from comparison of the measured and the calculated resonant frequencies that the interval between the calculated consecutive frequencies is still larger than the measured one which indicates that the assumed tube length is still too small and therefore, the applied end corrections are still insufficient.

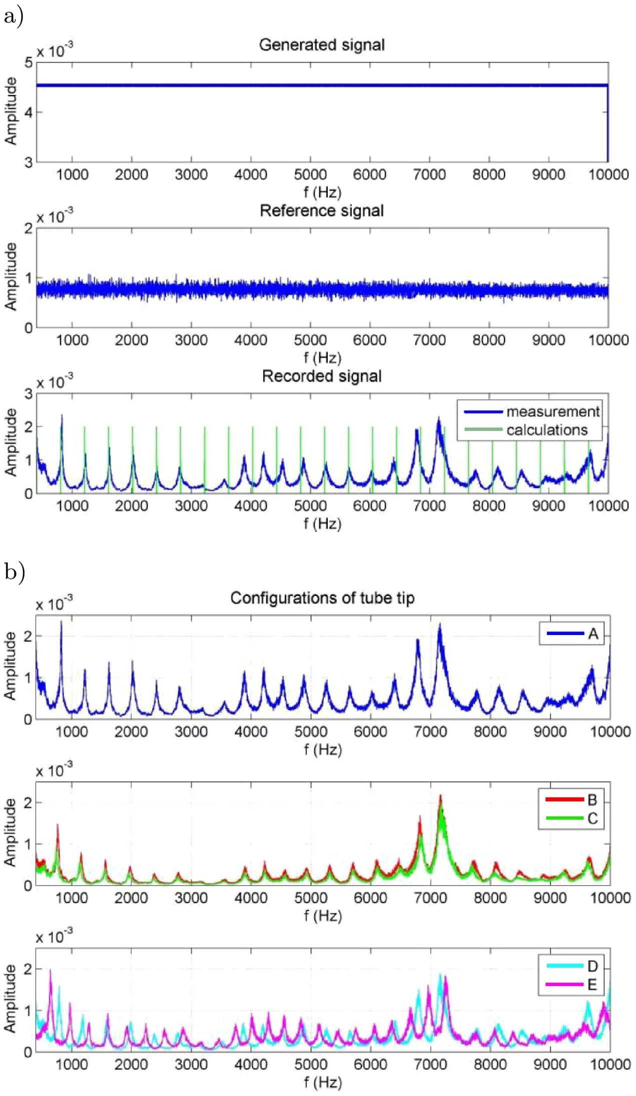


Fig. 4. a) Spectra of the generated signal, the reference signal, and the resulting signal registered in free field conditions for the model tube outlet in configuration A (plain outlet); b) spectra of signals registered for all the five tube outlet configurations of Fig. 2.

From the plot of the registered signal, the resonance frequency value $f_{\text{res}} = 7155$ Hz has been determined for which a maximum of amplitude occurs.

Figure 4b shows spectra of signals measured for different configurations of the point source modeling the tube outlet. It can be seen that the proposed modifications of the tube outlet do not eliminate the disadvantageous resonance effect to a satisfactory degree. However, the presence of the tube resonances minima has not significantly affected the sound pressure measurements. The analysis has been carried out with the resolution of 1 Hz and the frequency interval between the consecutive resonant frequencies is much smaller than between the modes cut-off's. Thus, for each mode it is possible to select several frequencies for which signal-to-noise ratio is sufficiently high to assure reliable experimental data. The best choice is to select frequencies for which the resonance maxima occur. Similar results were obtained when measuring sound radiation from tube tips provided with perforated spheres, so they are not discussed further in the present study. It may by therefore claimed that it is possible to generate a signal composed of combinations of frequencies corresponding to subsequent cut-off frequencies of Bessel modes, optionally with some additional limited intervals of lower and higher frequencies encompassing them. Another method to eliminate the effect of resonance occurring in the tube on measurement results could involve implementation of a normalization procedure consisting in dividing the measured signal representing the acoustic field radiated by the waveguide outlet by the spectrum of the signal emitted by outlet of the tube modeling a point source registered in the free field conditions.

3.2. Directivity patterns

Directivity patterns were measured in two perpendicular planes (horizontal and vertical) in order to verify omnidirectionality of different tube tip configurations. Measurements of the wave radiated outside from the tip of the tube were taken with the use of B&K 4183 1/2″ microphone that was positioned on the waveguide axis on a 0.89-m long arm with angular resolution of 5° in the range ±165°. Schematic diagram of the measuring set-up is presented in Fig. 1. Figure 5 shows such directivity patterns for three frequencies selected from lower ($f = 435$ Hz), middle ($f = 4760$ Hz), and upper ($f = 9995$ Hz) range of the generated signal and tube tip terminations defined in Fig. 1.

Analogous directivity patterns obtained for the sound wave radiated from tube tips provided with terminations F1–F3 shown in Fig. 3 are presented in Fig. 6.

Analyzing results of measurements obtained for various modifications of the tube tip modeling a point sound source it can be noted that the proposed technical solutions show basically no improving effect on either registered signal spectra or directivity patterns. The variants least useful from this point of view are those involving perforation, both in the form of holes made in the end section of the tube (Fig. 3) and pro-

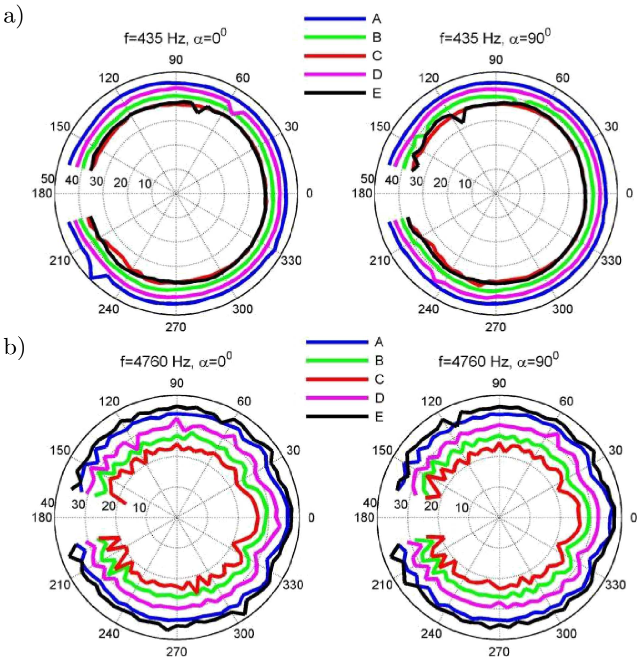


Fig. 5. Acoustic pressure directivity patterns in dB scale obtained for tube tips modified according to Fig. 2 for frequencies: a) 435 Hz, b) 4760 Hz, c) 9995 Hz.

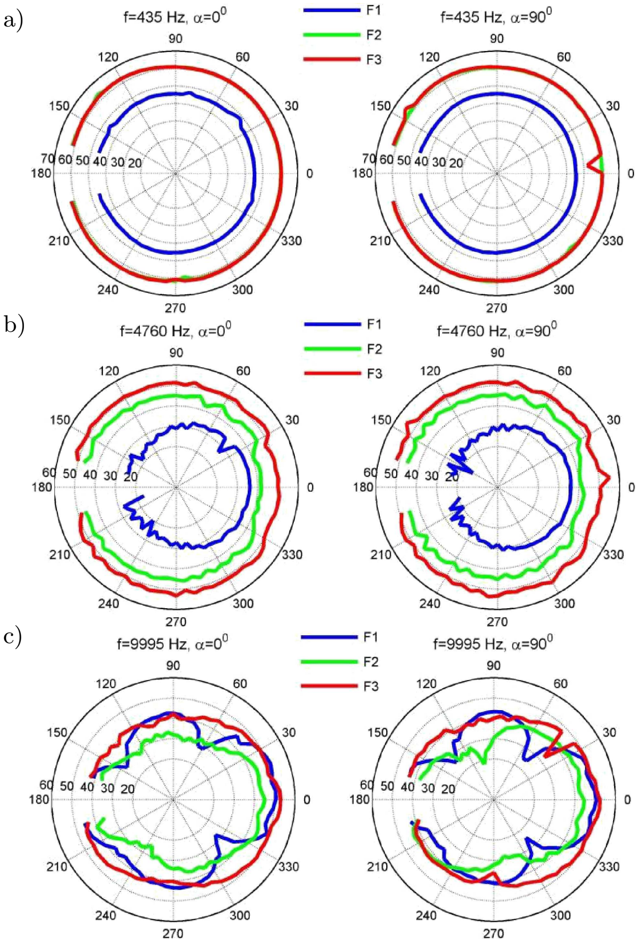


Fig. 6. Acoustic pressure directivity patterns in dB scale obtained for tube tips modified according to Fig. 3 for frequencies: a) 435 Hz, b) 4760 Hz, c) 9995 Hz.

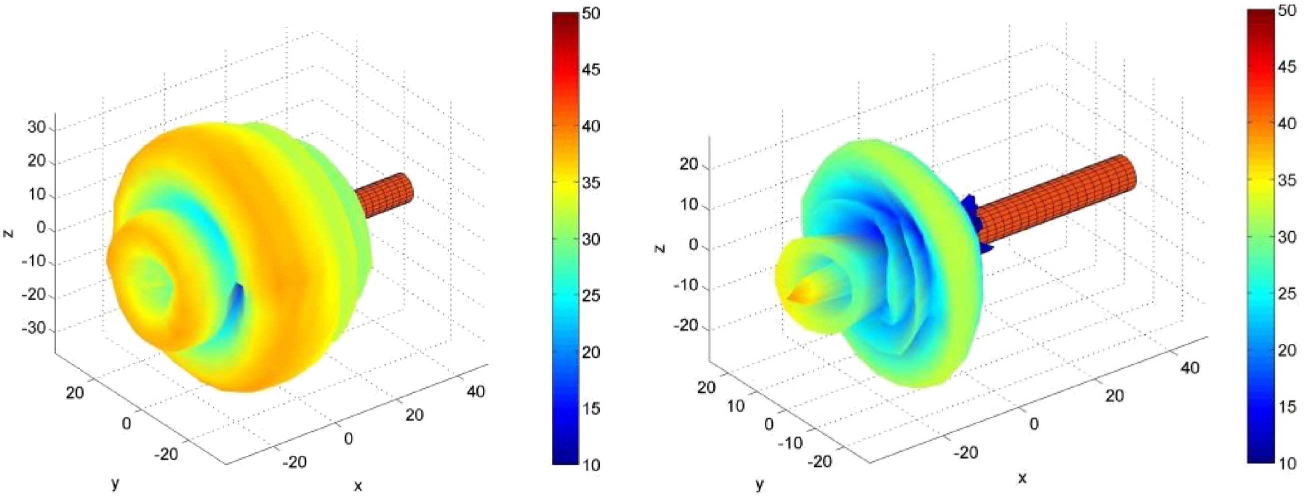
vided in a sphere attached to or encircling the tube outlet. In the case of perforated tube tip (modification E), resonance features show the largest amplitudes compared to other tip modifications, and directivity patterns for higher frequencies are no longer omnidirectional. The tube tip variants most usable as point source models are: modification A (with plain tube outlet) and modification D (with spiral insert), especially because of omnidirectional pattern of the emitted sound wave. Directivity properties of the wave radiated from the tube tip encircled by sphere with 57 holes (variant F1) turned out to be the most suitable compared to the two other models tipped with perforated spheres. To sum up, from among all variants and modifications of thin tube outlets examined from the point of view of their suitability for the purpose of modeling the point source, the variant denoted A, i.e. the plain tube outlet with unmodified circular orifice, seems to be the most favorable.

4. Field disturbance caused by a microphone

As it has been already mentioned in Introduction, another source of discrepancy between theoretical predictions and in-duct experimental data comes from the finite size of the measuring device – a microphone or intensity probe. By comparing the power radiated from the waveguide outlet in both situations it was possible to determine the acoustic field disturbance occurring as a result of placing a microphone inside the waveguide. Figure 7 shows 3D plots of directivity characteristics for selected excitation frequencies.

The measurements were carried out on a 2-m long pipe with radius $a = 0.1498$ m and the upstream end provided with anechoic termination housing the sound source and able to rotate within the 360° range of the azimuthal angle. The B&K 4183 1/2″ microphone was located on 0.89-m long arm. Precision of its positioning in horizontal plane was ensured by using a turntable

a) $ka = 7.26$, $f = 2653$ Hz b) $ka = 22.57$, $f = 8247$ Hz



c) $ka = 7.26$, $f = 2653$ Hz d) $ka = 22.57$, $f = 8247$ Hz

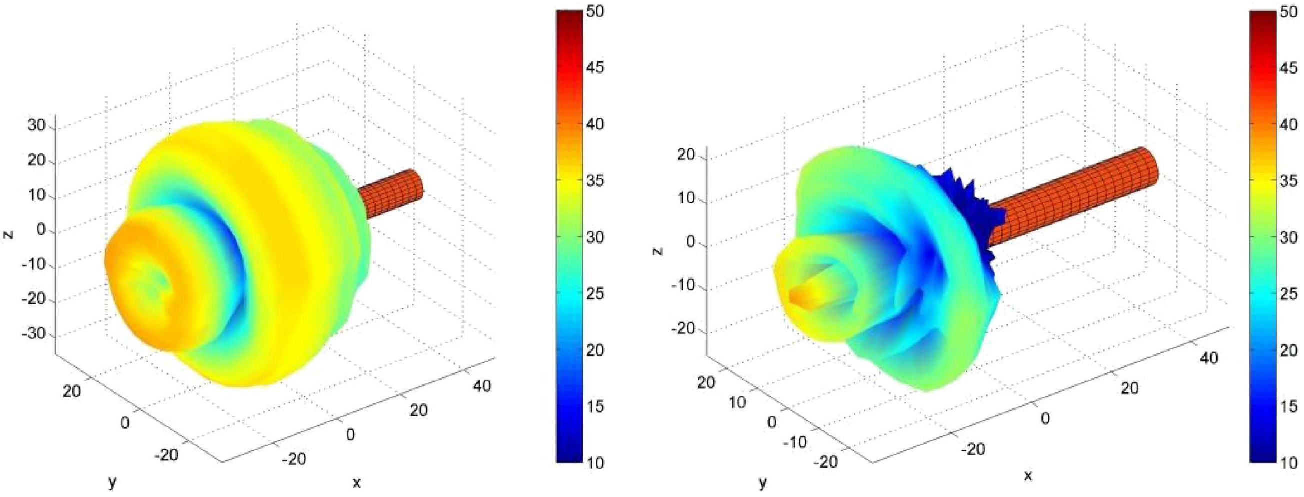


Fig. 7. Directivity patterns of the wave radiated by the waveguide outlet in dB scale: a), b) without, and c), d) with the measuring device mounted inside.

with angular resolution of 5° in the range ±165° of the polar angle which, in combination with rotary motion of the sound source, allowed to take measurements of 3D directivity characteristics.

Based on these directivity patterns, the total power of the wave radiated from the waveguide outlet has been calculated in two cases, i.e. with and without microphone placed inside the waveguide with the measuring frame introduced into and retracted from the duct.

It follows from analyses carried out in the framework of this study that presence of the measuring probe inside the model waveguide has virtually no effect in the form of a disturbance of the acoustic field in the frequency ranges 400–7100 Hz and 7400–10000 Hz at axisymmetrical excitation (Fig. 8a). The most significant effect of presence of the measuring probe can be seen in the frequency range 7100–7400 Hz. The same calculations were carried out for asymmetrical excitation (Fig. 8b) as a result of which even less noticeable effect of the measuring device on the radiated acoustic power value was observed.

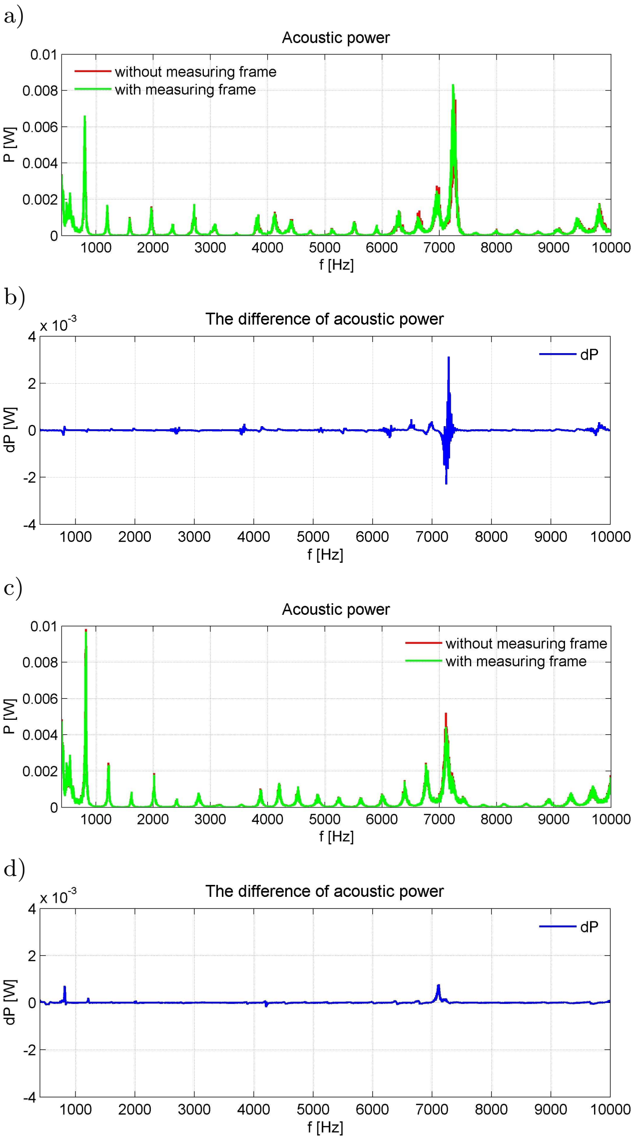


Fig. 8. A comparison of values of the acoustic power radiated by the waveguide outlet in two cases, with and without the measuring microphone placed inside the waveguide; a), b) axial, and c), d) non-axial excitation; lower panels show the differences.

Further, single-number values representing the total power for the whole frequency range and axisymmetrical excitation were calculated. With no microphone inside, the measured power level was 124.6 dB, compared to 124.7 dB with the microphone present in the duct. In the case of asymmetrical excitation, the corresponding power levels were 124.6 dB and 124.4 dB, respectively. The maximum observed difference of the level of total power radiated from the waveguide outlet was therefore 0.2 dB and seems to be sufficiently small to claim that the microphone placed inside the waveguide did not introduce any significant changes of this quantity.

5. Conclusions

As it has been shown in one of papers published within the framework of the same research project (Snakowska *et al.*, 2014), it is possible to construct the so-called single mode synthesizers, i.e. planar matrices of point-like sound sources located on a cross-section of a model of the circular duct, and generate selected single wave modes with such matrices to a satisfactory accuracy provided a certain minimum number of point sources is used depending on the combined order (radial and circumferential) of the required mode. Single mode synthesizers can be used to examine modal properties of various in-ducts features, such as e.g. mufflers, directly, i.e. by measuring reflection and transmission coefficients for the incident wave comprising a single mode and reflected/transmitted wave constituting a sum of all cut-on modes.

To apply the proposed method in practice, it is necessary to solve some technical problems. One of them consists in finding a way to simulate a point harmonic sound source, i.e. construct a sufficiently precise model of the acoustic monopole. The other technical challenge is connected with providing a measuring system allowing to scan the acoustic field inside a duct model with sufficient accuracy.

On the grounds of experiments aimed at determining feasibility of the proposed method of examining in-duct systems with the use of single mode synthesizers it can be concluded what follows:

- The outlet of a thin tube, the acoustic volume output of which is driven by means of a loudspeaker connected via an adapter, can be used in practice as a model of the acoustic monopole with sufficient accuracy within the examined frequency range, according to results of experiments carried out in free-field conditions. One may therefore expect that matrices of such sources will perform well as synthesizers of selected single modes used to examine properties of various in-duct systems and thus verify theoretical models of such systems.

- With the proposed measuring system, it is possible to measure distribution of the sound field inside a model of hard-walled circular duct with satisfactory accuracy. Tests carried out in the far field radiated from outlet of such model in the anechoic chamber proved that introduction of the proposed measuring frame holding small microphone and allowing to scan the field inside the duct results in a disturbance represented by a fraction of the order of a tenth of a decibel in terms of total radiated power.

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