The effect of cylindrical waveguide outlet features on the directivity pattern

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Summary
One method of influencing noise emission properties of acoustic duct outlets consists in shaping their directivity patterns according to specific needs such as, for instance minimising noise emitted to inhabited areas. As the rigorous analytical solutions are known for flanged/unflanged cylindrical outlets only, for more complex duct termination geometries it is necessary to use approximate solutions or advanced numerical methods.
The paper presents a number of directivity patterns obtained on the grounds of both laboratory measurements and numerical simulations for circular duct outlets characterised with various geometrical features for which analytical solutions, due to their complexity, are not known.
In the experiments, the examined systems were excited with point source located axisymmetrically or non-axisymmetrically in the vicinity of duct's anechoic termination. Registered directivity patterns were compared to results of simulations carried out with the use of the finite elements method. The aim of the presented study is to apply the results obtained to construct outlets of duct-like systems according to specific needs.

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1. Introduction

In the variety of problems considered within the scope of Duct Acoustics, only a few have been solved rigorously by means of analytical methods. Furthermore, these solutions require, in general, imposing some idealised conditions concerning, for example, geometry of the system (infinite/semi -infinite duct, infinite flange, constant cross section, no curves, etc.), features of structures and boundaries (soft, hard, locally reacting material, etc.), medium parameters (inviscid, homogenous, without flow or with uniform flow, etc.) or sources (monopoles, dipoles, etc.). For more complicated duct-like systems such as these encountered in practice, to mention only heat, ventilation, and air-conditioning (HVAC) systems, but also jet engines operating inside cylindrical casings, the solutions can be obtained by the use of numerical methods [1–6] which gain continually increasing importance. These frequently applied in acoustics are: the finite element method (FEM), the boundary element method (BEM), the finite difference method (FDM), the weighted residual method (WRM), the Galerkin method, and related techniques [7, 8]. The possibility of solving more and more complex problems by using these methods is closely related to increase in computing capacity.

Outlets of the above-mentioned devices are typical sources of environmental noise and therefore any attempt to reduce the sound level emitted by them is considered significant. One method of influencing noise emission from duct outlets consists in selecting adequate outlet geometry. Analytical solutions of the sound radiation from cylindrical duct outlets are obtained only for two extreme situations, namely for the duct provided with infinite rigid planar flange [9] or without any flange [10–12]. For more complex geometrical forms, advanced numerical methods have been used. And so, Dalmont et al. [5] investigated various flanges that can be found, in particular, in wind musical instruments, by means of BEM and FDM methods,. The paper was oriented at calculating the open-end correction with sufficient accuracy to determine the resonant frequencies, as the exact theoretical values are known only for

flange either infinite [9] or absent [13, 14]. Flanges with different geometries (horn, cylinder, sphere, circular, or rectangular) and widths were considered assuming the plane wave heading only towards the duct termination. Lidoine et al. [4] took into account finite duct-wall thickness and its lip shape on the far-field radiation.
The paper presents a number of directivity patterns obtained on the grounds of both laboratory measurements and numerical simulations for circular duct outlets characterised with various geometrical features for which analytical solutions, due to their complexity, are not known.

2. Physical modelling

2.1. Physical model design

The measurements were carried out in the 340-m^3 anechoic chamber operated by the Department of Mechanics and Vibroacoustics, AGH USC in Cracow. The main component of the set-up was a model of cylindrical rigid-walled waveguide made of PVC pipe with inner radius a = 77 mm, 3.2-mm thick walls, and total length of the main pipe, composed of a number of exchangeable segments, amounting to about 2700 mm. One end of the pipe was provided with anechoic termination to simulate conditions prevailing in the semi-infinite waveguide. To the other end, 700-mm long termination segments with diameter and wall thickness the same as those of the main pipe and were attached by means of a plug-and-socket connector. Ends of these final segments were given different geometries modelling thus semi-infinite circular ducts with different outlets.
The source of the acoustic wave was a model of the acoustic point source (monopole) in the form of outlet of a thin aluminium tube with inner diameter a_s = 10 mm and length of about 400 mm connected via an funnel-shaped adapter with a loudspeaker. Such source was located in the above-mentioned anechoic termination of the model, flush with its face on the side directed towards the outlet, in two different positions: symmetrically, on the duct axis, or asymmetrically (non-axially), i.e. outside the duct axis, and more precisely, at half the distance (a/2) from the axis of the pipe.
Earlier tests carried out in the same anechoic chamber with the above-described model of acoustic point source proved that in the frequency range 400 Hz–10 kHz the directivity patterns of the model source radiating in simulated free-field conditions are omnidirectional to a satisfactory accuracy.
In order to prevent direct transmission of sound from the loudspeaker along the waveguide and the sound emitted from the loudspeaker's back side along or around the duct model, the space between the source mount and the funnel-shaped adapter as well as this between the loudspeaker and the rear end of the duct model was filled with mineral wool. Construction of the anechoic termination consisted in providing the rear portion of the PVC pipe with perforation and wrapping it with a thick layer of mineral wool. The whole model is reposed horizontally on rollers and can be rotated around its longitudinal axis by an arbitrary angle. Measurements described in this paper were carried out with resolution in the polar angle $\Delta\theta$ = 15°.

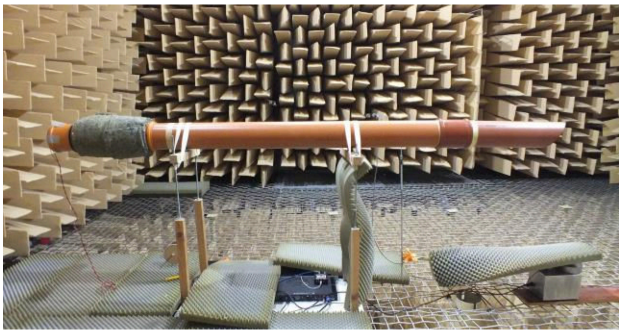

Figure 1. A view of the measurement set-up with Type I termination mounted in position corresponding to θ = 180°.

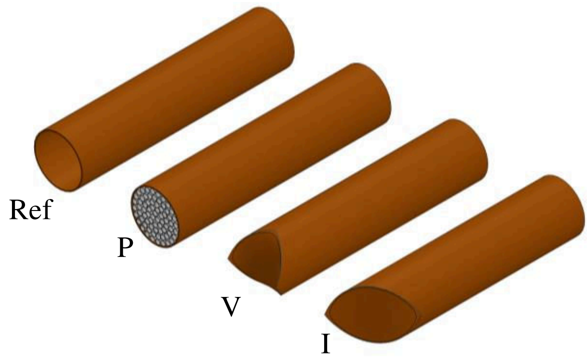

Figure 2. The four examined duct termination types.

2.2. The measuring apparatus

The measuring microphone was mounted on a boom with the length of L = 930 mm. The boom was mounted to a turntable rotation of which was controlled via a RS232 port with the use of a program developed and run in MATLAB environment. This allowed to measure directivity patterns of the duct model outlet with resolution in the azimuthal angle $\Delta\varphi = 5°$ with the range $[-170°, +170°]$. The excitation signal used in the measurements was a multi-tone containing sinusoidal signals with frequencies from the range 400 Hz–10 kHz separated by 1 Hz, with equal amplitudes and random phases. Measurements were carried out for three modifications of the duct outlet, denoted with letters P, V, and I in Fig. 2, and compared to the measurement obtained for the reference (Ref) outlet which was simply a plain circular termination of the pipe. Type P duct termination was obtained by inserting 74 pipes, each 160-mm long, with inner and outer radius of 7 mm and 8 mm, respectively, tightly fit to the inner surface of the duct and to each other. In Type V termination, the final section of the pipe was cut off along two perpendicular planes symmetrical with respect to the duct axis. Type I termination was obtained by cutting the tube along two helixes drawn on the cylinder surface and crossing at angle 90° to each other and 45° to the cylinder's generatrices.

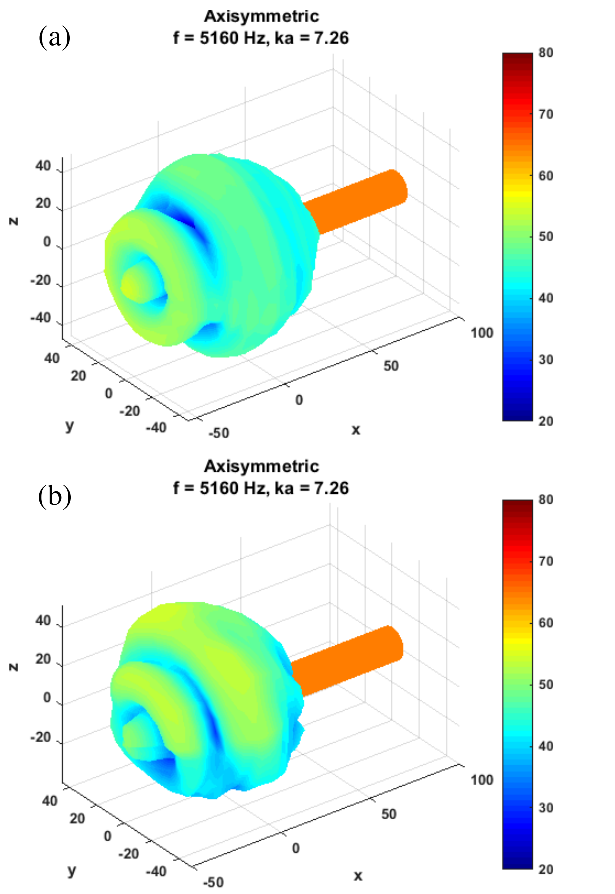

Figure 3. The acoustic pressure distribution patterns measured for two outlet geometries: (a) Type R (reference) and (b) Type I (obliquely inclined) for the same reduced frequency value ka = 7.26 and axisymmetrical excitation.

2.3. Measurement results

The plots shown in the following figures present a selection of example directivity patterns measured in the above-described experimental set-up for different values of the reduced frequency ka. Figure 3, for instance, shows the acoustic pressure distribution pattern taken with Type Ref and Type I duct terminations for the reduced frequency value of 7.26 which is higher than the cut-on frequency for the radial mode (0, 2). It can be observed that for Type I termination, the sound directivity pattern is biased in direction corresponding to orientation of the oblique outlet surface.

In Fig. 4, 3D directivity patterns taken for $ka = 4.01$ and Type I duct outlet are compared for field excitation by the source located asymmetrically (out of the duct axis) and symmetrically (on axis). Presence of mode (2, 0) excited in the first case is clearly visible.

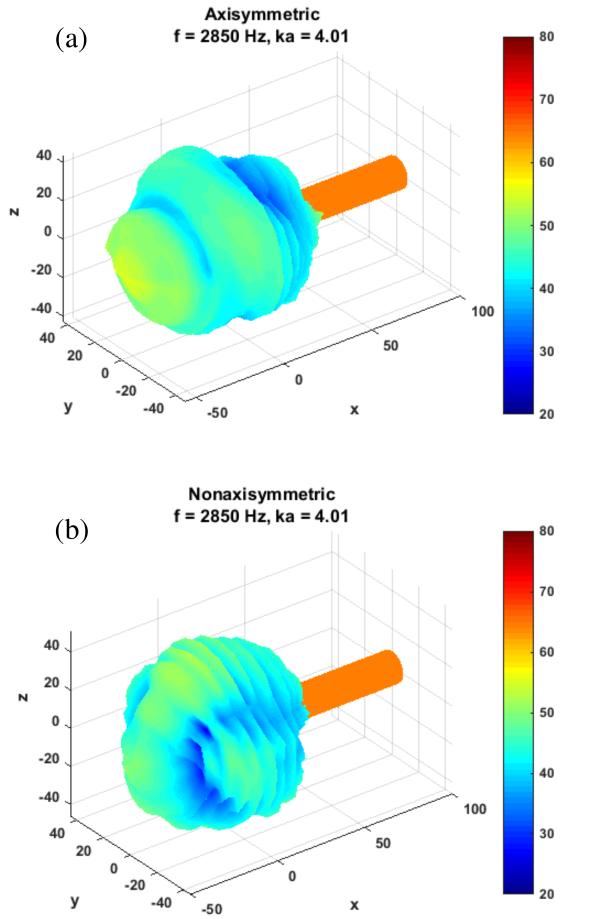

Figure 4. Measurement results for ka = 4.01, axisymmetrical excitation (a) and non-axisymmetrical excitation (b) for Type I duct outlet geometry.

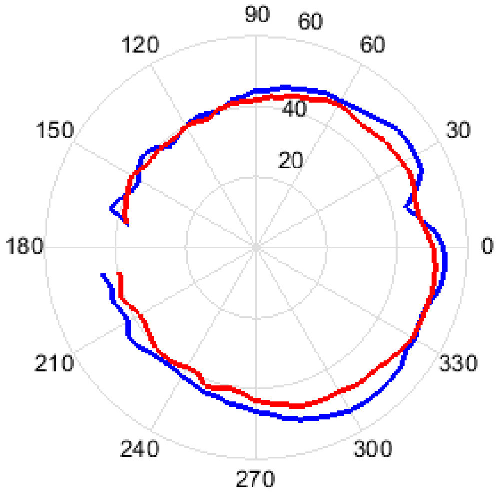

Figure 5. Acoustic pressure values averaged over the polar angle θ for Type Ref (blue) and Type P (red) duct terminations at the reduced frequency value *ka* = 7.26 and non-axisymmetrical excitation.

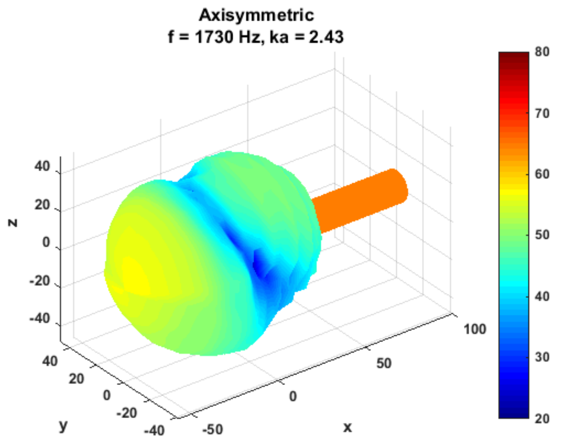

Figure 6. The acoustic pressure distribution pattern measured for the reduced frequency value *ka* = 2.43, axisymmetrical excitation, and Type I (inclined) duct termination.

The plots of Fig. 5 show the acoustic pressure values measured outside the duct and averaged over the polar angle θ for the model with two different termination types: Ref (plain circular outlet) and P (outlet packed with a bunch of thin tubes). The measurements were taken for the reduced frequency value *ka* = 7.26 and axisymmetrical excitation.

3. Numerical modelling

3.1. Model description

Numerical simulations by means of the finite element method were carried out with the use of Abaqus software made available by AGH's Cyfronet computing centre. The numerical model represented a 2000-mm long hard-walled cylinder with radius a = 77 mm. The surrounding medium was modelled as a sphere with radius of 1000 mm centred at the crossing point of the cylinder axis and the plane tangent to the duct outlet. Both boundary surfaces were connected by means of Tie-type bonds on the waveguide outlet surface. As the materials parameter characterising the acoustic medium, density 1.2 kg/m^3 and sound speed 340 m/s have been adopted. On the cylinder's rear cross-section as well as on the surface of the surrounding sphere, the boundary condition of the 'non-reflecting' type was imposed, while the cylinder walls were modelled as 'perfectly reflecting' surfaces. The excitation was defined as the acoustic pressure value at the node located 100 mm from the non-reflecting rear end of the duct either on its axis or at half distance between the axis and the cylinder surface (a/2 from the axis) which reproduced the situation existing in the course of measurements carried out with the physical model. Depending on the frequency for which simulations were performed, elements of the mesh superposed on the model had different dimensions chosen in such the way that the condition

$$L_{max} \leq \lambda/6 \qquad (1)$$

was always met, where L_{max} is the maximum size of the mesh element and λ is the wavelength corresponding to the frequency for which the simulation was carried out.

3.2. Simulation results

Figure 7 shows 3D representations of results of FEM simulations carried out for axisymmetrical excitation and Type I duct termination at the reduced frequency value *ka* = 2.43 which falls above the cut-on frequency of mode (1, 0). Due to symmetrical location of the source, this mode cannot be excited. Comparison of results obtained from the simulation on one hand and from measurements on the other (Figs. 6 and 7, respectively) for the same frequencies, excitation types, and outlet geometries it can be stated that the results demonstrate satisfactory consistency.

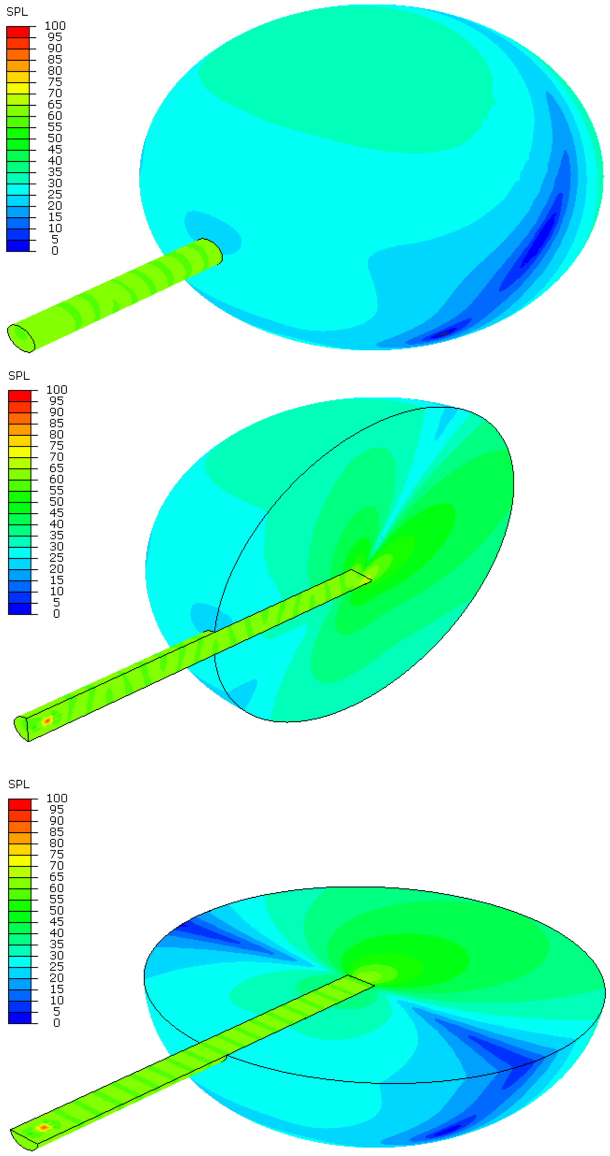

Figure 7. SPL distribution over a sphere with radius 1 m for the duct with Type I duct termination and the reduced frequency value ka = 2.43 obtained by means of FEM simulation.

4. Conclusions

The study described above concerned experiments with a model of semi-infinite circular duct provided with terminations characterised by different geometries and excited by a model of the acoustic monopole located inside the duct either axially or non-axially. The physical model was constructed and tested in an anechoic chamber. Further, a numerical model of the same acoustical system was developed by means of the finite element method and the results obtained by means of these to different modelling techniques were then compared to each other. In accordance with predictions of the analytical theory of cylindrical waveguides, with increasing values of the reduced frequency, acoustic pressure distribution patterns outside the cylindrical duct become more and more complex.

Four different types of duct outlet geometry were considered. Measurements of the acoustic field radiated from physical models of such outlets as well as corresponding simulations were carried out for two different positions of the point source inside the duct, on and out of axis.

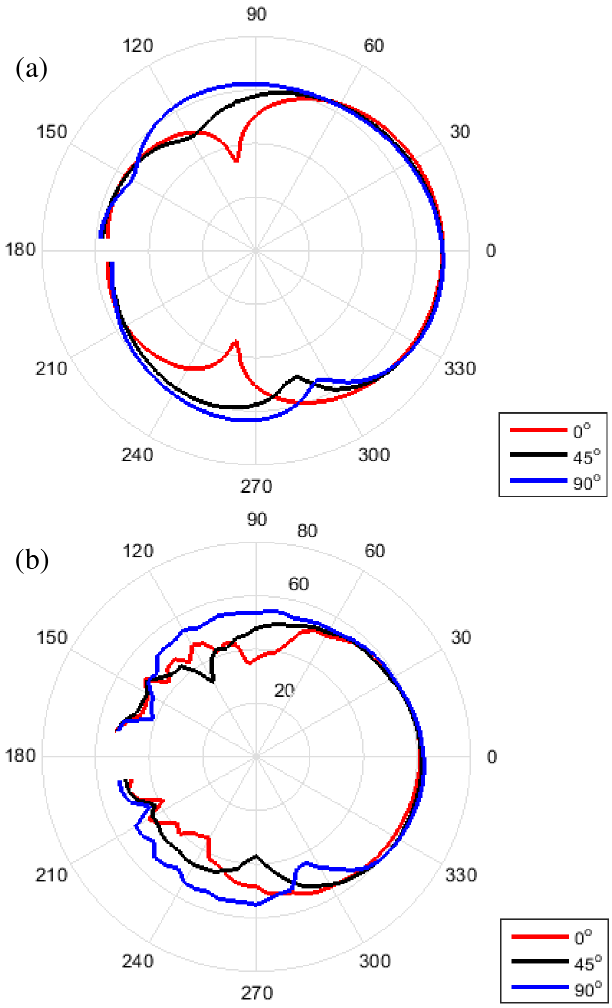

Figure 8. A comparison of results obtained from measurements and simulations for Type I duct termination, axisymmetrical excitation, ka = 2.43, and three values of angle θ.

Possible sources of discrepancies between results of measurements performed on the physical model and those obtained from the strict theory and simulations include: inaccurate microphone positioning with respect to waveguide axis; error in angular position of the model rotated along its axis; sound source positioning with respect to the mode axis; and/or inaccuracies to which different duct termination models were machined.

It has been demonstrated that by modifying geometry of the cylindrical duct outlet, it is possible to alter the directivity pattern of the sound radiated from the system. The effect is hardly noticeable for low frequencies below the cut-on frequency of any mode other than the plane wave ($ka < 1.84$) and directivity patterns obtained for all of the modified duct outlets were nearly omnidirectional.

Application of the outlet model cut obliquely along two perpendicular helices (Type I) results in corresponding distinct bias of the directivity characteristics. By packing the duct outlet with a system of tubes with small diameter (Type P) it is possible to obtain directivity patterns similar to those observed below the cut-on frequency for the first mode in a wider range of frequencies. Some other results of both physical and numerical modelling will be shown during presentation of this paper at the conference.

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References

[1] X. X. Cheng, X. Zhang, C. L. Morfey, P. A. Nelson: A numerical method for computation of sound radiation from an unflanged duct. J. Sound Vib. 270 (2004) 573–586.

[2] V. Ahuja, Y. Ozyoruk, L. Long: Computational simulations of fore and aft radiation from ducted fans. AIAA Paper 2000–1943 (2000).

[3] Y. Ozyoruk, L. Long: Computation of sound radiating from engine inlets. AIAA Journal 34(5) (1996).

[4] Lidoine S., Batard H., Troyes S., Delnevo A., Roger M.: Acoustic radiation modelling of aeroengine intake comparison between analytical and numerical methods AIAA–2001–2140AIAA/CEAS, Collection of Technical Papers 1 (2001).

[5] Dalmont J. P., Nederveen C. J., Joly N.: Radiation impedance of tubes with different flanges: numerical and experimental investigations. J. sound Vib. 244(3), (2001) 505–534.

[6] Dykas S., Wróblewski W., Rulik S., Chmielniak T.: Numerical method for modeling of acoustic waves propagation.Archives of Acoustics, 35(1), (2010) 35–48.

[7] Munjal L. M.: Acoustics of Ducts and Mufflers. Wiley 2014.

[8] S. Marburg, B. Nolte: Computational Acoustics of Noise Propagation in Fluids. Springer, 2010.

[9] Y. Nomura, I. Yamamura, S. Inawashiro: On the acoustic radiation from a flanged circular duct. J. Phys. Soc. Japan 15 (1960) 510–517.

[10] Homicz G. F., Lordi J. A.: A note on the radiative directivity patterns of duct acoustic modes. J. Sound Vib. 41(3), (1975) 283–290.

[11] Snakowska A., Idczak H., Bogusz B.: Modal anlysis of the acoustic field radiated from an unflanged cylindrical duct theory and measurement. Acustica/Acta Acustica 82(2), (1996) 201–206.

[12] Snakowska A., Jurkiewicz J.: Efficiency of energy radiation from an unflanged cylindrical duct in case of multimode excitation. Acta Acustica/Acustica 96 (2010) 416–424.

[13] Snakowska A., Jurkiewicz J., Smolik D.: Open end correction for arbitrary mode propagating in a cylindrical acoustic waveguide. Acta Phys. Pol. A 120 (2011) 736–739.

[14] Levine H., Schwinger J.: On the Radiation of Sound from Unflanged Circular Pipe. Phys. Rev. 73(4), (1947) 383–406.