



THE LOUDSPEAKER SYSTEM EQUIPPED WITH ORGAN TUBES

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ABSTRACT

The electro-acoustic system is presented, which due to innovated design has sound similar to organ, especially in low and medium frequencies. The system consists of loudspeakers in bass-reflex or labyrinth enclosures with an additional system of organ tubes. Open and closed tubes of different length are used, which help to create variable essential resonance frequencies and variable timbre overtone sounding. The calculations show that this design improves the frequency response of the system for low frequencies. Produced experimental model is represented by a 3-way loudspeaker system with phase-inverter. Enclosures for woofers and midrange loudspeakers are provided with the open and closed tubes. The bandwidth of the system is 46-5700 Hz. Bandwidth of detached tubes is matched in such a way that their frequency characteristics are covered at -3dB level. Estimated results are confirmed with measurement. System has almost flat frequency response within the 20 Hz-10 kHz range. Acoustic system creates sound in which relevant organ features can be distinguished: rich bass outlining, brightly emphasizing of medium frequencies. Relatively slow onset of organ tubes creates especially gorgeous sound of organ music and monumental orchestral compositions.

The design of the loudspeaker system equipped with resonant tubes is developed. The tubes can be placed on the wall of the enclosure as well as they can load directly the loudspeaker diaphragm. The system is similar to the system in vented box, except the equivalent circuit of the tube. In vented box the tube has the form of a canal and its acoustic impedance has inertial character. In described system the length of the tube is compared with the wavelength, and its acoustic impedance has resonant character. As the result, the radiated sound becomes enriched, and the dips on the frequency response of the loudspeaker can be corrected. Closed and open tubes of various length are used in the system. It allows to create different resonant frequencies and different timbre of radiated sound. The general equivalent circuit of the tube is represented as T-shaped four-pole, shown on Fig. 1.

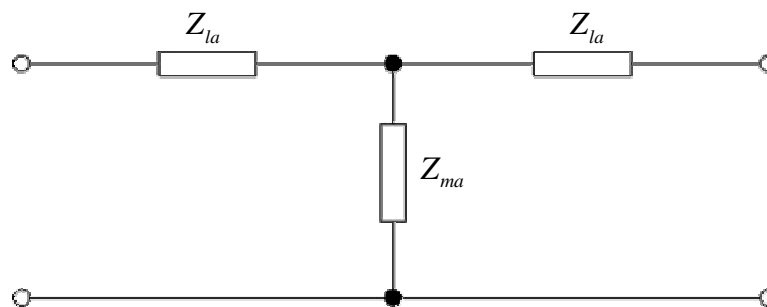


Figure 1. - General equivalent circuit of the tube

The elements of this system are calculated from the following formulas:

$$Z_{la} = \frac{1 - \cos kl}{\frac{i \sin kl}{r_0 c_0 / S}}; \quad (\text{Eq. 1})$$

$$Z_{ma} = \frac{-1}{\frac{-i \sin kl}{r_0 c_0 / S}}, \quad (\text{Eq. 2})$$

where: l – length of the tube;

S – cross-section area;

$k = \frac{\omega}{c_0}$ – wave number;

r_0 and c_0 – air density and sound speed,

In a case of low-frequency approximation (when $l \ll \lambda / 4$, λ – wavelength):

$$Z_{la} = j\omega \frac{m_{ab}}{2}; \quad (\text{Eq. 3})$$

$$Z_{ma} = \frac{1}{j\omega C_{ab}},$$

where $m_{ab} = \frac{r_0 l}{S}$ – acoustic mass;

$C_{ab} = \frac{lS}{r_0 c_0^2}$ – acoustic compliance of the tube.

Equivalent electrical circuit of the opened tube, taking into account losses, is shown in Fig.2

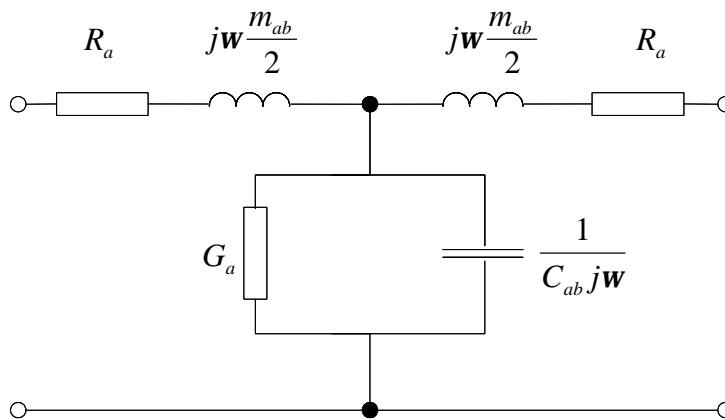


Figure 2. Equivalent circuit of the open tube for low frequencies

The acoustic resistance and conductivity are given by the following equations:

$$R_a = \frac{2prl}{S^2} \sqrt{pfr_0 m},$$

$$G_a = \frac{2prl(h-1)}{r_0 c_0^2} \sqrt{\frac{I_H \cdot 2pf}{2c_p r_0}},$$

where r –radius of the tube; $m = 1,86 \cdot 10^{-5} \frac{N \cdot s}{m^2}$ – viscosity coefficient; $I_H = 23,03 \cdot 10^{-3} \frac{W}{m \cdot K}$ – heat conduction coefficient; $h = 1.4$ – adiabatic constant; $c_p = 1005 \frac{J}{kg \cdot K}$ – air specific heat under constant pressure.

The open end of the tube is terminated by the radiation impedance:

$$Z_{ar} = R_{ar} + jX_{ar};$$

where active and reactive components and co-pendulous mass are:

$$R_{ar} = \frac{r_0 c_0}{S} \cdot \frac{(kr)^2}{4}, \quad X_{ar} = \frac{wm_c}{S^2}, \quad m_c = 2r_0 r^3$$

The equivalent electric circuit of the closed tube is shown in Fig .3.

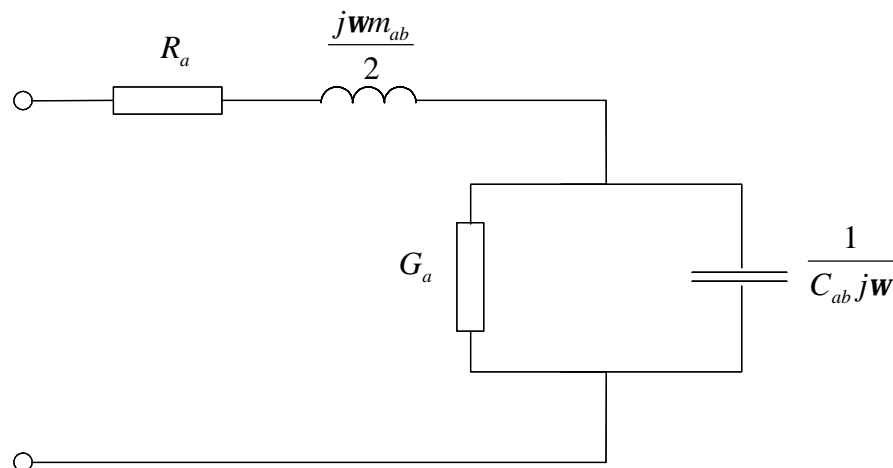


Figure 3. The equivalent electric circuit of the closed tube

The dimensions of the tubes sizes were chosen in such a way that their bandwidths cover the useful frequency range of the loudspeaker.

The frequency responses of the gain for four tubes are presented in Fig. 4, their parameters are collected in Table 1. The gain is defined as the volume velocity under unit pressure excitation. Full equivalent electric circuit of the system, which consists of loudspeaker in closed enclosure and four tubes situated at the wall of enclosure is shown in Fig 5. The sizes of tubes are presented in Table 1. The parameters of the mechanical system are denoted as r_0 , m_0 , and c_0 . The acoustic compliance of the closed box is denoted as C_F .

The radiation acoustic impedance of loudspeaker z_{ea} and radiation acoustic impedance of the tube z_{et} are drawn with dotted line.

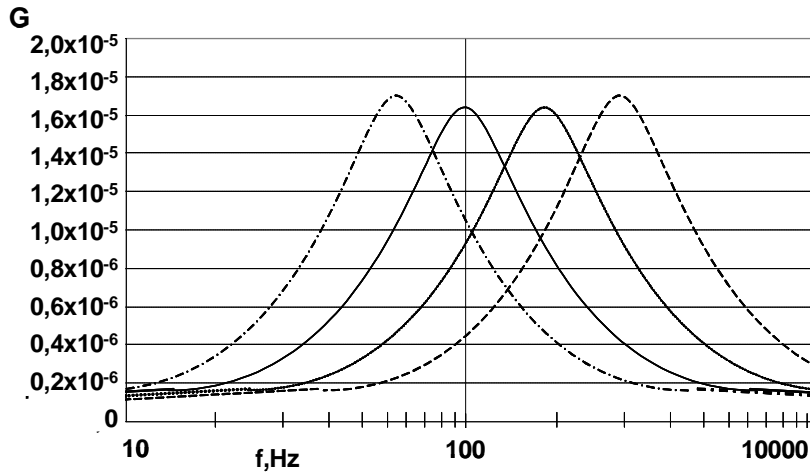


Figure 4. Frequency responses of four tubes

Table 1. The parameters of the tubes from Figure 4

?	Length, m	Radius, m	Resonant frequency, Hz
1.	1,72	0,055	49
2.	0,8	0,042	106
3.	0,4	0,03	213
4.	0,2	0,02	425

Full equivalent electric circuit of the system, which consists of loudspeaker in closed enclosure and four tubes situated at the wall of enclosure is shown in Fig 5. The sizes of tubes are presented in Table 1. The parameters of the mechanical system are denoted as r_0 , m_0 , and c_0 . The acoustic compliance of the closed box is denoted as c_F .

The radiation acoustic impedance of loudspeaker z_{ea} and radiation acoustic impedance of the tube z_{et} are drawn with dotted line.

The experimental model of the loudspeaker system with organ tubes have been developed. It consists of woofer of type 75-HDL, midrange loudspeaker of type 20-HDM and tweeter of type 15-HDH. The boxes for woofer and midrange loudspeakers are equipped with opened and closed tubes. The parameters of tubes are shown in Tables 2 and 3. Tubes are made from birch veneer sheets of 2 mm thick. The outlet of open tubes are cut with angle of 45° . The tubes closed at the end have an outlet near connection with the enclosure.

Table 2. Parameters of the tubes connected to the enclosure of the woofer

?	1st eigenfrequency, Hz	Bandwidth, Hz	Tube length, m	Tube type
1.	54,4	46,0 – 64,5	1,6	Closed
2.	76,5	64,5 – 91,0	1,12	Closed
3.	107,5	91,0 – 127,5	1,56	Open
4.	151,5	127,5 – 179,5	1,10	Open
5.	212,8	179,5 – 252,5	0,786	Open
6.	300,0	252,5 – 355,0	0,56	Open
7.	421,0	355,0 – 500,0	0,4	Open

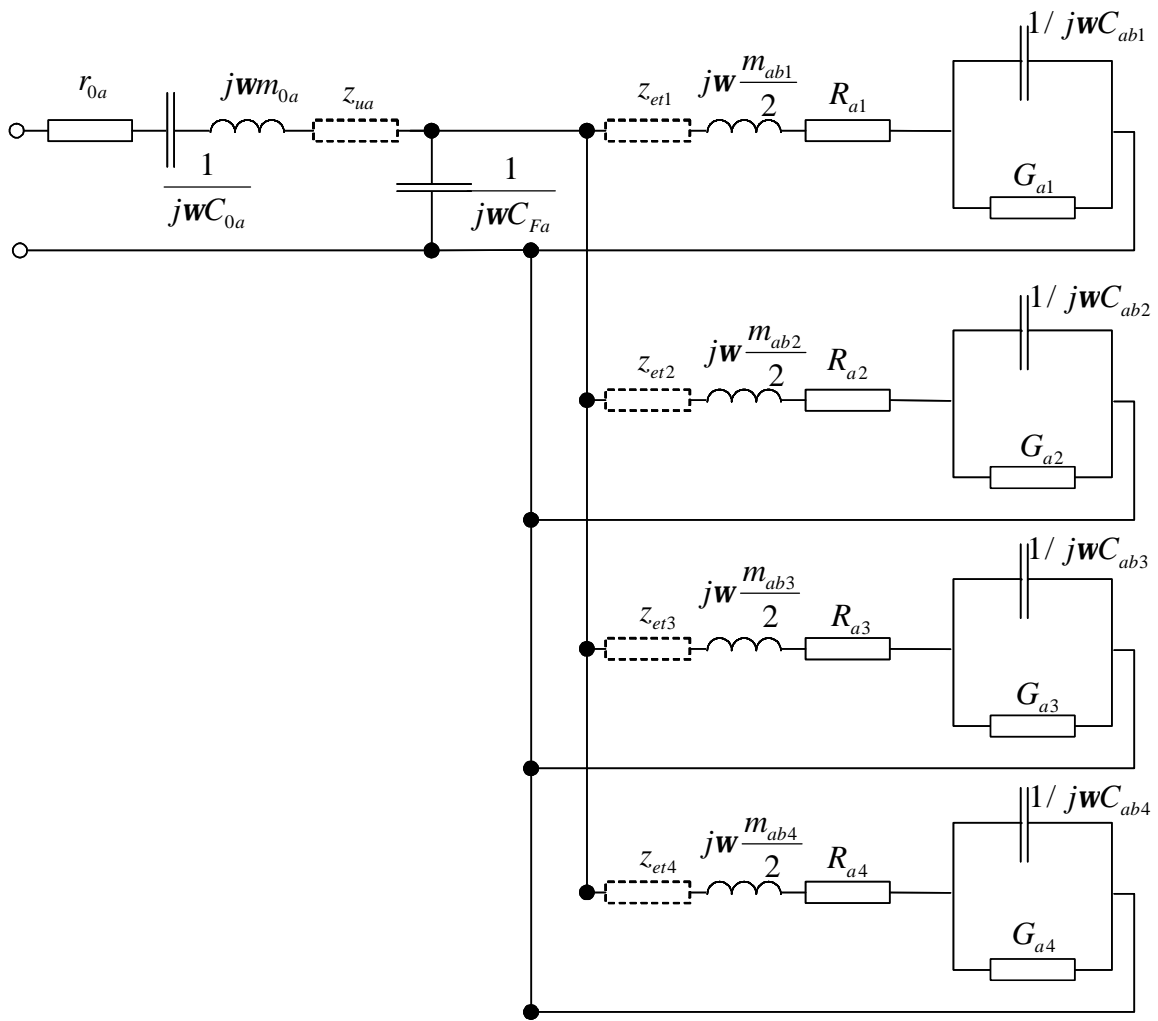


Figure 5. The equivalent circuit of loudspeaker in closed box equipped with four tubes

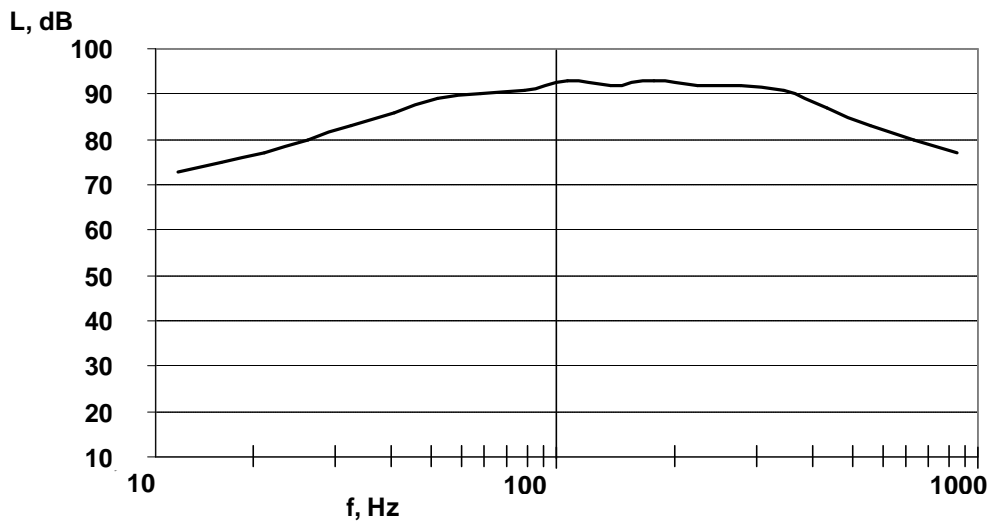


Figure 6. Calculated frequency response of the system

Table 3. Parameters of the tubes connected to the enclosure of the midrange loudspeaker

?	1st eigenfrequency, Hz	Bandwidth, Hz	Tube length, m	Tube type
1.	600	500 – 714	1,28	Open
2.	853,7	714 – 1020	0,2	Open
3.	1219	1020 – 1457	0,14	Open
4.	1728	1457 – 2043	0,1	Open
5.	2430	2049 – 2882	0,09	Open
6.	3417	2882 – 4053	0,05	Open
7.	4800	4053 – 5700	0,035	Open

The measured frequency response of the system, normalized to its nominal efficiency is presented in Fig. 7.

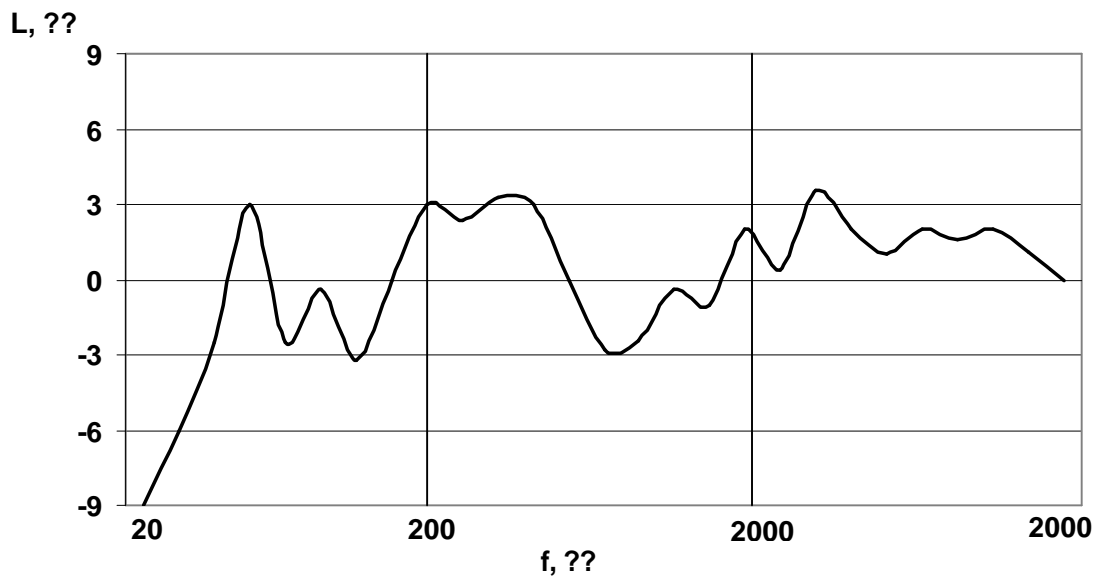


Figure 7. Frequency response of the actual system

The efficiency of the system is higher than the system without tubes approximately by 10 dB and lower limiting frequency decreased 1.5 -2 times.

Designed system satisfies requirements for Hi-Fi equipment. It creates sound in which relevant features of the organs can be distinguished: rich bass outline and brightly emphasized medium frequencies. Relatively slow attack phase in organ tubes creates especially gorgeous sound during reproduction of organ music and monumental orchestral compositions.