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HIGH-END 3-WAY SPEAKERS BASED ON TRANSMISSION LINE SYSTEM[**]

1. INTRODUCTION

Building a speaker in a professional way requires a lot of technical knowledge. In spite that building speakers by amateurs is very popular. Up to now, in Poland we could only get loudspeakers made by Tonsil , so speaker designers didn't have much choice. We also had the same problem, while constructing crossovers. But now things have changed. There are new companies on the market that sell Scan-Speak, Seas, JBL, KEF, Cervin Vega, or Focal loudspeakers. They are not cheap - but you can't build a low-cost High-End speaker. It's good to build speaker sets, because you can never find two speakers that sound the same. While making my own set I paid attention to price and quality (especially the latter one). That's why my midrange and tweeter are made by Focal. Focal company is famous for its loudspeakers built especially for High-End speaker systems. JM LAB uses Focal loudspeakers in its High-End sets. The Tonsil woofer that I used didn't make my set sound worse; only made my speakers cost less. However, we can still ask why I used a low magnetic parameter loudspeaker. The solution is in the box construction - transmission line system.

2. SCOPE OF ANALYSIS

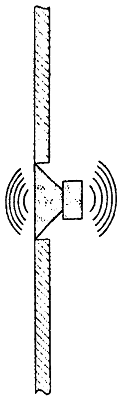
Fig.1 The infinity separated wall.

The most widely used and popular loudspeaker is a dynamic loudspeaker. While in use the dynamic loudspeaker produces pressure on both sides of the membrane and the air waves (that come out of the membrane) are in opposite phase. It is necessary not to let them interfere. We have to define the infinity separated wall. However, it is impossible to build such a wall. This wall should separate the wave energy produced by the loudspeaker membrane (Fig. 1). There is no sense in constructing such big speaker boxes today. It could not provide proper phase shift at low frequencies. In case of tweeter the construction of the loudspeaker closes the rear side of the membrane; it also mutes the wave. To make the midrange and (especially) woofers sound right special means have to be taken. There are two ways of constructing the boxes that solve the problem of the wave energy produced by the rear side of the membrane:

- using the switch-phase boxes that radiates the energy out (in the given frequency range)
- using the damping circuits

Some research eliminates the woofer box. The most popular boxes are:

- closed
- bass-reflex (also with passive radiators)
- band-pass
- labyrinth (also with transmission line)
- tube

Parameters of the box are connected with the loudspeaker's characteristics. The most important electric and mechanical loudspeaker parameters were coded in the Thiele-Small parameters:

1. f_S - resonance frequency
2. Q_{TS} - Q of a loudspeaker at Fs in free air considering both its electrical and mechanical resistance.

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3. V_{AS} - the volume of air having the same compliance as the suspension of a loudspeaker (liters)

$$f_s = \frac{1}{2\pi\sqrt{C_{MS} \cdot M_{MS}}} \tag{1}$$

C_{MS} - the mechanical compliance of a loudspeaker suspension (meters per Newton).
M_{MS} - the mechanical mass of a loudspeaker diaphragm assembly including air load (kilograms).

$$Q_{TS} = \frac{Q_{MS} \cdot Q_{ES}}{Q_{MS} + Q_{ES}} \tag{2}$$

Q_{MS} - the Q of a loudspeaker at Fs considering only its mechanical (non-electrical) resistance.
Q_{ES} - the Q of a loudspeaker at Fs considering only its electrical (non-mechanical) resistance.

Below the f_S level the efficiency of transforming the electrical energy into acoustical decreases. Frequency transform characteristic in resonance frequency range and below (Fig. 2) depend from $Q_{TS.}$

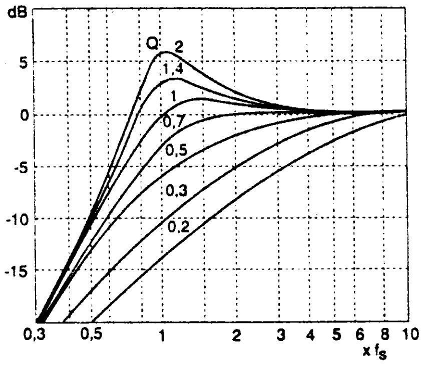

Fig. 2 The theoretical characteristics of a loudspeaker for different values of Q at the resonance frequency f_S.

$$V_{AS} = \rho_o \cdot c^2 \cdot S_b \cdot C_{MS} \tag{3}$$

ρ_o= density of air 91,18 kg/m^3
c = velocity of sound in air (345 m/s)
S_b = the piston area of a loudspeaker (square meters).
C_{MS} = the mechanical compliance of a loudspeaker suspension (meters per Newton).

The box with the transmission line system is put into practice very seldom. There are some problems to bring them into general use. To build a Bass-reflex or closed box speaker small volume is sufficient (several liters). Small dimensions of the speaker box causes lack of sub-low frequencies. It also determined bass quality. The concept of the transmission line makes it necessary to construct relatively big boxes. Additionally, this big size box is not just a simple „box”. It is full of all kinds of partitions and deflections. In general, assembling the transmission line box requires big amounts of materials and a lot of work. While constructing bass reflex, band-pass or closed box the builder uses mathematical and physics formulas. In case of the transmission line boxes no algorithms have been elaborated. Its performance is characterized by a range of acoustic laws. Best High-End boxes are created during a long process of attempts and failures.

The idea of the transmission line is similar to the infinity separated wall. A long tunnel behind the loudspeaker filled with damping material is supposed to absorb all wave energy radiated by the rear side of the membrane (Fig. 3). Such is the concept of the perfect transmission line. However, the real tunnel is never infinite and therefore it is not able to damp all the radiated energy. The tunnel entrance radiates some of the energy outside. In order to present the meaning of this effect it is necessary to study what happens to the waves in a definite tunnel. Let us suppose that the tunnel is not damped. The wave radiated by the rear side of the membrane is shifted in phase on the way loudspeaker - tunnel entrance. The shift depends on the tunnel length and wave-length, that is: wave frequency.

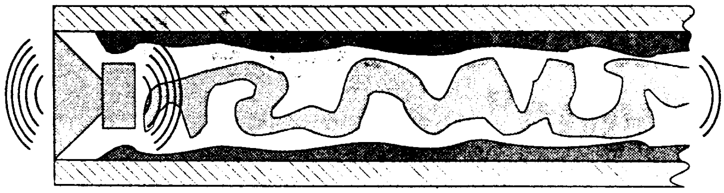

Fig. 3 The very long tunnel with damping material is the base of the concept of the transmission line.

To shift the wave 180° (to ensure the same phase of radiating the front side of the membrane and tunnel exit) at the frequency of 20 Hz, the tunnel length is supposed to be half the wave-length of this frequency, that is: 8,6 m. It is very difficult to make it. On the basis of the vector calculus we can observe that when the phase shift is 60° (the tunnel length is equal 1/6 wavelength), the total radiation is the radiation of the front side of the membrane (Fig. 4).

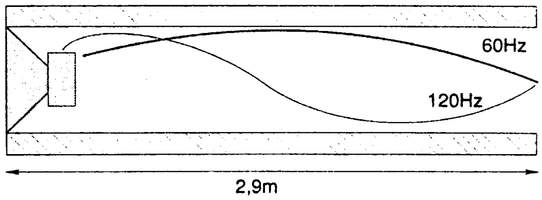

Fig. 4 The shift of the wave radiated by the rear side of the membrane in the tunnel of the length 2.9m appears at: 60° for 20 Hz, 180° for 60 Hz and 360° for 120 Hz.

For 20 Hz the proper tunnel length is only 2,9 m. The maximum radiation appears at the shift close to 180° (Fig. 4), that is at the frequency 3 times higher: 60 Hz. We can see that at the frequency characteristic graph at the point where frequency range is relieved (Fig. 5).

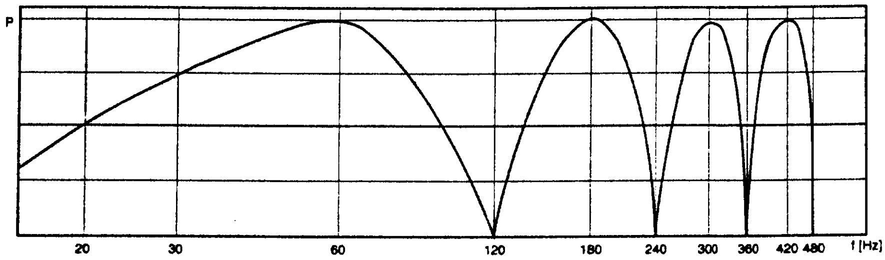

Fig. 5 The resultant system frequency characteristic: front of the membrane - exit of the tunnel at the tunnel of the length 2.9m.

While moving up the frequency scale some serious problems connected with the tunnel functioning can be observed. At the frequency two times higher than 60 Hz (when the phases were consistent) the entire wave is placed along the tunnel, that means that the shift is 360° (180° phase shift to the front side of the membrane). The tunnel exit radiates waves in the opposite phase to the front side, so the energy neutralizes. We can see it as a subsidence on the graph. Resonance (uneven multiplies 60 Hz) and anti-resonance (opposite phases even multiplies 60 Hz) that appear later disturb the linearity at all frequency ranges produced by the loudspeaker. Damping the tunnel is low efficient as far as the sub-frequencies are considered, it works much better at the range of hundreds Hz (Fig. 6).

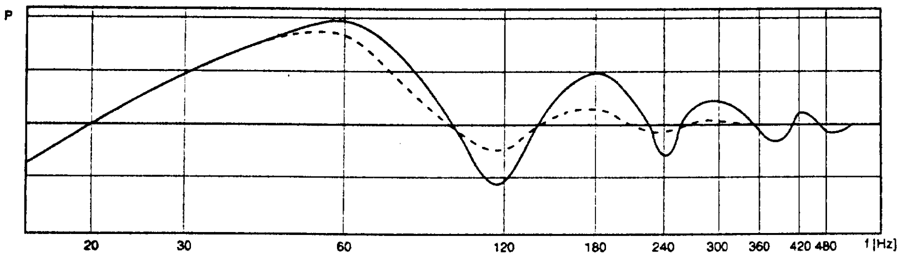

Fig. 6 The system frequency characteristic at the damping tunnel (low damping-solid line, high damping-dashed line).

Real performance of the well-built transmission line can be better then the „perfect" one because of the energy gain at the low frequency range. All other advantages of the line such as the fact that the air is neither compressed or uncompressed are preserved. Wall vibrations are eliminated (compare with closed box Fig. 7).

The most important problem is eliminating the first anti-resonance (range over 100 Hz - in our case 120 Hz). It is important to consider another resonance occurrence - at the frequency when a quarter of the wave is placed in the tunnel the reduction of the piston speaker amplitude move occurs. Most of the energy is radiated out through the tunnel exit (similar to the resonance frequency of bass-reflex box). The tunnel length which corresponds to the quarter wave resonance is most often connected with the frequency resonance of the loudspeaker. That damps the biggest vibrations of the piston at this frequency range, it also gives the optimal bass performance. Lower tuning (longer tunnel) doesn't bring any advantages because the efficiency decline of the loudspeaker. For example, proper tunnel length for the woofer with the resonance frequency of 30 Hz is 2,9 m (wavelength 30 Hz - 11,5m.). While building the transmission line we can neglect V_{AS}. This parameter is important only when the loudspeaker is suspended on the air cushion. When the transmission line is considered the loudspeaker is freely suspended and the increase of the resonance frequency and Q do not appear. One of the most important loudspeaker parameters is Q_{TS}. Q_{TS} should be contained within the range of 0,5...0,7 that is the desired Q of the ready-to-use set. It assures right pulse properties at the optimal frequency characteristic.

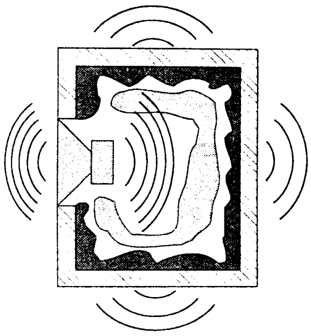

Fig. 7 The vibrations of the walls in closed box

It seems strange, but we can use poor loudspeakers with small magnet in the transmission line (unacceptable in case of bass-reflex). These loudspeakers are usually cheaper. In general, assembling the volume of transmission line box depends on the piston area of the loudspeaker. In case of bass-reflex and closed box there is no direct connection between the box volume and the size of the loudspeaker. Even if the loudspeaker is big and the parameters are satisfactory, it can be used in a relatively small box. It is acceptable because there is no connection between the wavelength and the dimensions of the box. In case of the transmission line the section of the tunnel can't be smaller then the piston area of the loudspeaker. The loudspeaker that we want to use in the transmission line system should be defined by some parameters. The woofer should have very low resonance frequency and work in very large-scale of amplitude: firstly by the big mass of the loudspeaker piston, secondly by the coil much longer then the gap. While building the transmission line we can't forget about standing waves. We eliminate the waves by variable section of the labyrinth. The tunnel should reduce the area of the section from the loudspeaker to the exit of the tunnel. We can reduce the volume of the box at about 20% by using the tunnel with smaller section. In some cases we must bend the tunnel, but it is better not to do it too many times. The exit of the tunnel can be located in any place of the box, but the quality of bass depends on its location. For example, when we place the exit of the tunnel on the top of the box we can move the speaker set near the wall. When it's located in the lower part of the box, especially from behind the resound bass may dominate (bigger radiation) and we can't move the speaker so close to the wall. We can meet with following constructions on the market (Fig. 8).

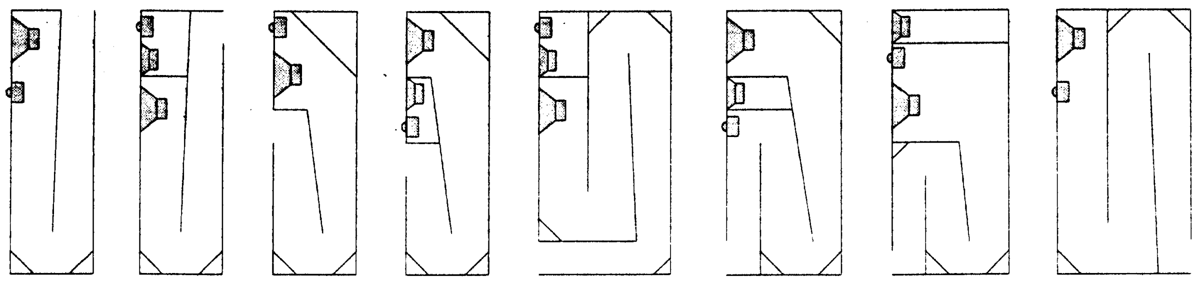

Fig. 8 The different speaker boxes based on a transmission line for 2 and 3-way constructions

Of course there are some connections between all loudspeakers in the box. We must remember about specially separated cabin for midrange. This cabin can't disturb acoustic wave run along the tunnel. The next problem is the right choice of the kind of damping. The first operation is to cover all partitions with a few centimeters of dense sponge, the second - to fill up the tunnel with material of small density. The best result can be achieved with the long-hair sheep wool at a density of 8 kg m^3. We should attach the wool to the partitions. I said some words about anti-resonance. The worst is the first anti-resonance. In our case it is placed at 120 Hz and depends on the total length of the tunnel. Some companies and constructors make special exertions to eliminate it. Damping is one of the ways to solve the problem, but it doesn't eliminate it completely. The best solution is to make a crossover with the lower x-over before the first anti-resonance. In this case the bass loudspeaker works as a sub-woofer loudspeaker. Then we should use a relatively big midrange loudspeaker (about 16 cm). The second solution is in cunning construction of the labyrinth. We can form the partition separate the tunnel suitably. The most of acoustic pressure produced by the rear side of the membrane radiates from the loudspeaker to the exit of the tunnel along the longer way (where the cutting is the highest). Some part of the energy going along the short way where the opening decreases (Fig. 9). Then some part of the energy at the end of the tunnel which is going along the short way is in shift with the energy going along the longer way. It brings the smear of the anti-resonance on frequency characteristic. The other solution is to lead the energy from the rear side of the membrane along two different ways. They can be common on some part of the way (Fig. 10).

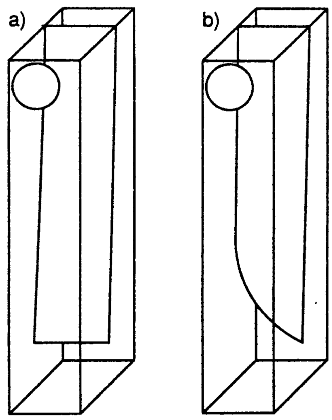

Fig. 9 a) typical construction b)construction with specially formed partition

3. RESULTS OF ANALYSIS

I should write some words about the woofer I used. I chose 20cm Tonsil woofer described by symbols GDN 20/60/3. It has low resonance frequency and comfortable value of Q_{TS}. The basic parameters of this loudspeaker are following:

- resonance frequency f_S=36 Hz
- Q_{TS}=0.45
- equivalent volume V_{AS}=70 dm^3
- sensitivity (1W/1m.) Sp=87 dB
- total power P=60W
- nominal impedance Zc=4Ω
- resistance of loudspeaker coil R_E=3.5Ω
- the piston area of a loudspeaker S=200cm^2

I used this woofer in frequency range to 200Hz, then I had to use a crossover coil with a big value of induction (about 10mH). The total Q_{TS} is growing because the coil has some resistance (Rs). We can define with good approximation the total value of Q_{TS}.

$$Q_{TS}' = Q_{TS} \cdot \frac{R_E + R_S}{R_E} \tag{4}$$

The resistance of the used coil is 0,5Ω then the corrected value of Q_{TS}' is 0.5 (the best for the right pulse properties). We don't need the precise value of Q_{TS}'. In case of the transmission line this parameter is superfluous. We need this value only to check if the loudspeaker fits to this kind of box (transmission line allows to use the loudspeakers of Q_{TS} value from 0.4 to 0.7). We don't need to calculate the equivalent volume V_{AS}, either. The most serious parameters are the resonance frequency and the piston area of the loudspeaker. We assume that quarter wave resonance in the labyrinth corresponds with the resonance frequency. It assures the best work conditions for the loudspeaker. The total length of the tunnel is corrected by 0.9 coefficient (in damping tunnel the velocity of acoustic wave decreases).

$$L_{TL} = \frac{C}{F_s \cdot 4} \tag{5}$$

$$L_{TL}' = 0.9 \cdot \frac{C}{F_s \cdot 4} \tag{6}$$

where L_{TL} - the total length of the labyrinth, L_{TL}' - the total corrected length of the labyrinth, C - velocity of sound in air (345 m/s)

$L_{TL}' = 2.15m.$

For the best transform efficiency for the lowest frequencies we have constructed the area of the exit of the labyrinth at about 200cm^2. The area behind the woofer should be twice more and we accepted the value of 400cm^2. The sections of the speaker box are shown in figure 11. There are two possible configurations of tweeter and midrange. If the speaker box is too high and the tweeter isn't on the level of the human ears we can exchange the tweeter with the midrange. We must remember that we can do that only when the lower x-over is set to a few hundreds hertz. If the x-over is higher and we have low-order crossover some negative relationships between them appear. The tweeter should be near the midrange. The speaker boxes are made of 19mm MDF material. The total volume of the labyrinth is about 64.5 dm^3. For example, if we want to use the same woofer in a closed box of Q_{TC}=0.7 (maximum flat characteristic) the required volume of the box is 64dm^3.

$$Q_{TC} = Q_{TC}'\sqrt{1+\frac{V_{AS}}{V_C}} \qquad (7)$$

V_C - the volume of the closed box at total damping $V_C=1.25V_C'$, where V_C' - real volume of the box
We can calculate the loudspeaker resonance frequency in closed box:

$$F_C = F_S\sqrt{1+\frac{V_{AS}}{V_C}} = 49Hz \qquad (8)$$

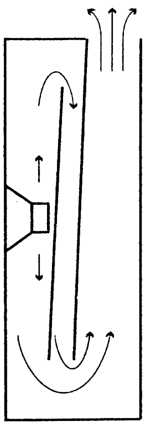
Fig. 10 The wave goes along two different ways.

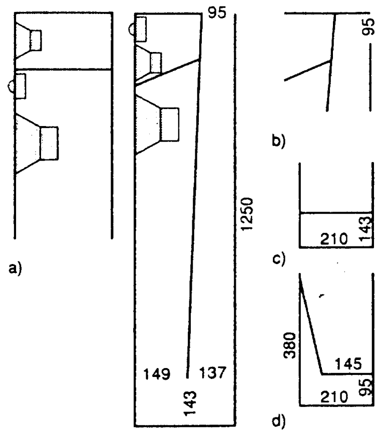

Fig. 11 GDN 20/60/3 in transmission line
a) the tweeter with the midrange exchange b) the exit of the tunnel from behind at the top of the box c) typical partition d) formed partition

We can compare the theoretical loudspeaker characteristic in infinity separated wall (F_S=36Hz ; Q_{TS}'=0.51), transmission line (2.15m. ; 64 dm^3) and closed box (F_C=49Hz ; Q_{TC}=0.7) (Fig. 12). As we can observe the woofer GDN 20/60/3 is the loudspeaker that can be successfully used in the transmission line. We may notice that the transmission line gives us best transformation for lower frequencies. If we have a loudspeaker with a larger value of Q_{TS} the profit is bigger and we can construct smaller boxes. For example, if we have a loudspeaker with all parameters the same as for GDN 20/60/3 only with higher value of Q_{TS}'=0.6 then the required volume of the box for Q_{TC}=0.7 should amount to 160cm^3. For the transmission line nothing changes. All loudspeakers frequency responses and crossover schema are shown in figures 13, 14, 15 and 16.

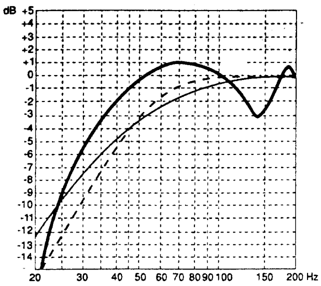

Fig. 12 The theoretical loudspeaker characteristic in infinity separated wall (thin line), transmission line (thick line), closed box (dashed line)

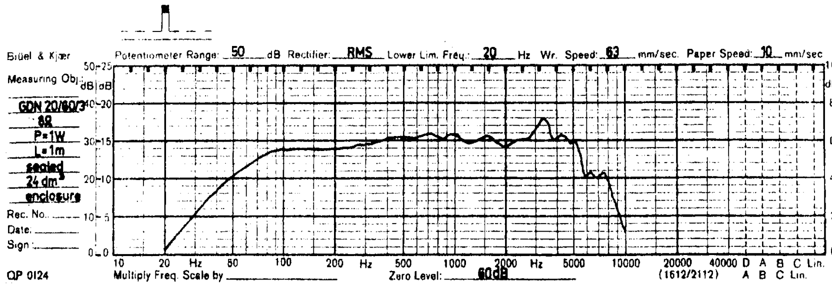

Fig. 13 The woofer GDN 20/60/3 frequency characteristic

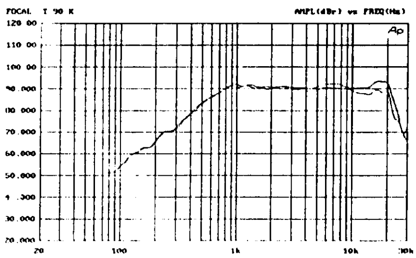

Fig. 14 The tweeter TC90K frequency characteristic

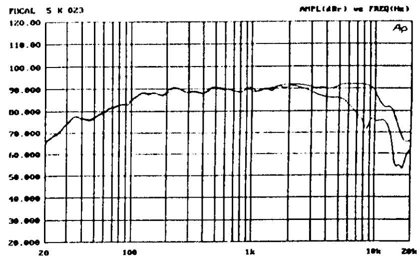

Fig. 15 The midrange 5K023 frequency characteristic

Crossover Network Components:

Lower frequency: 200 Hz
Upper frequency: 3kHz

3-way 2nd-order

C1=3.30µF;
C2=69.63µF;
C3=4.88µF;
C4=98.88µF
L1=0.85mH;
L2=7.97mH;
L3=0.65mH;
L4=6.40mH

Tweeter L-Pad:
R1=0.88 ohms; R2=64.89 ohms

Midrange L-Pad:
R1=0.47 ohms; R2=100 ohms

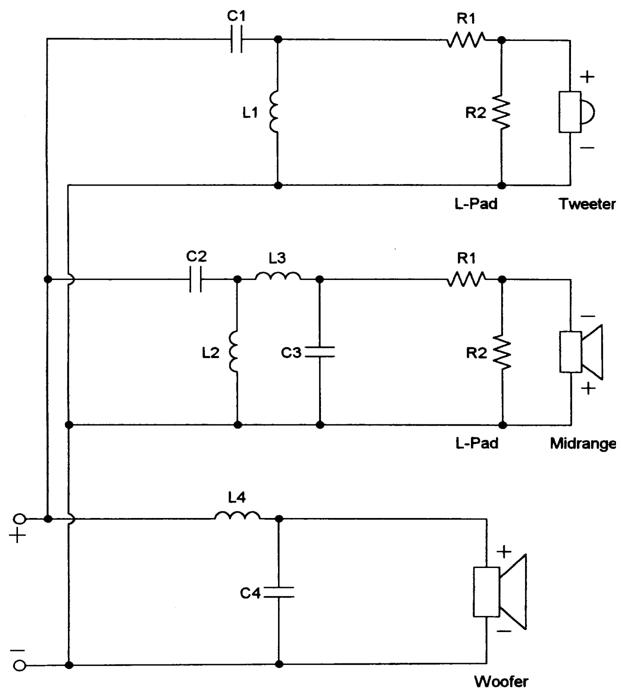

Fig. 16 The crossover schema

	Z [ohms]	R_e [ohms]	L_e [mH]	Q_{ms}	Q_{es}	sensitivity [dB]
Tweeter TC90K	8.0	6.0	0.08	4.713	1.178	91.5 (2.83V)
Midrange 5K023	6.0	5.3	0.40	1.819	0.310	90.5 (2.83V)
Woofer GDN 20/60/3	4.0	3.5	0.85	2.700	0.630	86.9 (1 watt)

Table 1 Tweeter, Midrange and Woofer parameters

4. CONCLUSIONS

The object of this publication was to prove that the best kind of box is transmission line system. It assures the best conditions for the woofer loudspeaker. It assures right pulse properties and to construct it we can use poor loudspeakers with small magnet. Unfortunately, this kind of box has serious faults. The volume of the box is relatively big and we struggle with some anti-resonance problems. The volume of the box corresponds with the piston area of a loudspeaker. If we want to get monumental bass from the woofer with the diameter of 30cm, we must build a box with the height of about 170cm. In the described example I used a 20cm woofer. The total height of the box is 120cm. So we don't need the support. I used a profiled partition to minimize the first anti-resonance. The midrange and tweeter are placed in one closed box. It was constructed to reproduce well the pulse properties (Q_{TC}=0.5). I used very linear loudspeakers. The lower x-over is 200 Hz and higher is 3kHz. The total sensitivity (2.8V / 1m) is 90.5 dB. So for very loud listening we can use a power amplifier with total power output of about 30W. The tunnel was bent at once. I used the long-hair sheep wool as the damping material. I located the exit of the labyrinth behind the box at the top part of it. It allows to manipulate the character and quantity of the bass by moving the box to (from) the wall. The crossovers are placed in midrange and tweeter boxes. The coils I used have very small dimensions and resistance. I obtained this effect because I used non-saturate transformer core. All capacitors I used are non-polar. The speakers are painted with white piano varnish.

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