Band-Pass Loudspeaker Systems with Single Vent

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Abstract – **In this work are presented theoretical analysis of characteristics of fourth order band-pass loudspeaker systems. Mathematical relationships are defined for calculating the electrical and acoustic characteristics of band-pass loudspeaker systems in linear modelling. Using the method of researching, for system is analyzed frequency, pulse and step characteristics.**

Keywords – **Band-pass loudspeaker systems, frequency curve, step and impulse response.**

I. Introduction

The Band-pass loudspeaker systems are known for a long time ago [11]. Band-pass loudspeaker systems are researched by Fincham [5], Geddes [8], Mallory [7], Sutphin [8], Berkhoff [9], Matusiak and Dobrucki [11] and others. Now these systems are used for low-frequency channel of: computer loudspeaker systems, auto audio systems and the soundtrack of TV, video and cinema systems.

Figure 1 presents a band-pass loudspeaker system with single vent.

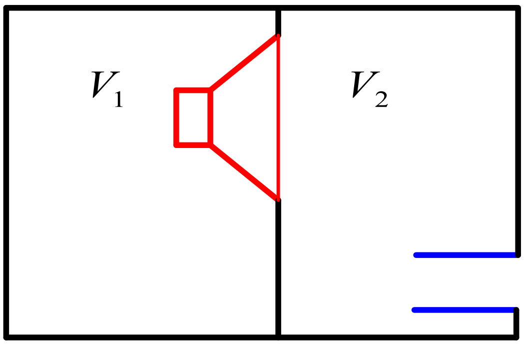

Fig. 1. Sketch of a double cavity single vented loudspeaker system

II. Glossary of Symbols

$B.l$ = *Force factor loudspeaker magnet system* [16], $T.m$

c = velocity of sound in air, $(c = 345)$, m/s [3]

C_{ms} = *mechanical compliance of driver suspension*, m/N [16]

$C_{вн}, C_{MES}$ = electrical capacitance due to driver mass, F $\left(C_{вн} = M_{ms}/(B.l)^2 = M_{as}.S_d^2/(B.l)^2\right)$, [3]

C_{as} = acoustic compliance of driver suspension, $\left(C_{as} = C_{ms}.S_d^2\right)$, m^5/N [3]

C_{ab1or2} = acoustic compliance of air in box V_1 or V_2 $\left(C_{ab1} = V_{1or2}/\rho_0.c^2\right)$, [7] m^5/N

e_g = open circuit output voltage of amplifier, V

i = imaginary factor, $\left(i = \sqrt{-1}\right)$

f = frequency, Hz

$K(s)$ = fourth order band-pass system response (transfer) function, $\left(K(s) = K_1(s).K_2(s)\right)$ [13]

$K_1(s)$ = second order low-pass transfer function

$K_2(s)$ = second order high-pass transfer function

L_e = *loudspeaker electrical inductance*, H [16]

$L_{вн}, L_{CES}$ = electrical inductance due to driver compliance [3], H $\left(L_{вн} = C_{ms}.(B.l)^2 = C_{as}.(B.l)^2/S_d^{\ 2}\right)$

M_{as} = acoustic mass of driver diaphragm assembly and air load, $\left(M_{as} = M_{ms}/S_d^{\ 2}\right)$, [3], kg/m^4

M_{ap2} = acoustic mass of air in vent, r - radius vent, L - length of vent, kg/m^4 $\left(M_{ap2} = \rho_0.(L + 0{,}85.r + 0.61.r)/\pi.r^2\right)$, [1, 7]

M_{ms} = *mechanical mass of loudspeaker diaphragm assembly including air load* [16], kg

p_0 = equivalent acoustic pressure, Pa $\left(p_0 = e_g.B.l/(R_g + R_e)S_d\right)$, [3]

Q_1 = box 1 Q at ϖ_S resulting from all losses, [3] $\left(Q_1 = \frac{1}{\varpi_S.C_{as1}.R_{atc}}\right)$, $\left(\frac{1}{C_{as1}} = \frac{1}{C_{as}} + \frac{1}{C_{ab1}}\right)$ [3]

Q_2 = box 2 Q at ϖ_B resulting from all losses, $\left(\frac{1}{Q_2} = \frac{1}{Q_L} + \frac{1}{Q_A} + \frac{1}{Q_P}\right)$ [4]

Q_A = box 2 Q at ϖ_B resulting from absorption losses, $\left(Q_A = \frac{1}{\varpi_B.C_{ab2}.R_{ab2}}\right)$ [4]

Q_L = box 2 Q at ϖ_B resulting from leakage losses, $\left(Q_L = \varpi_B.C_{ab2}.R_{al2}\right)$ [4]

Q_P = box 2 Q at ϖ_B resulting from vent frictional losses, $\left(Q_P = \frac{1}{\varpi_B.C_{ab2}.R_{ap2}}\right)$ [4]

R_e = *loudspeaker voice coil dc resistance* [16], Ω

R_g = amplifier output resistance [3], Ω

R_{ms} = *mechanical mass of loudspeaker suspension losses* [16], $N.s/m$, kg/s, $1N = m.kg.s^{-2}$

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R_{ab1or2} = acoustic resistance of box 1 or 2 losses [7] due to internal energy absorption, $N.s/m^3$

R_{atc} = total series resistance, fig. 7

$$\left(R_{atc} = R_{ab1} + R_{at} + R_{as} = R_{ab1} + \frac{R_{ms}}{S_d^2} + \frac{(B.l)^2}{(R_g + R_e)S_d^2} \right) [3, 4]$$

R_{al2} = acoustic resistance of box 2 losses [7] due to leakage, $kg/m^4.s$

R_{ap2} = acoustic resistance of vent losses, $kg/m^4.s$

R_{as} = acoustic losses [3], $N.s/m^5$

$$\left(R_{as} = R_{ms}/S_d^{\,2} = (B.l)^2 / R_{вн}.S_d^{\,2} \right)$$

$R_{вн}, R_{ES}$ = electrical resistance due to driver suspension losses[3], Ω

$$\left(R_{вн} = (B.l)^2 / R_{ms} = (B.l)^2 / S_d^2.R_{as} \right)$$

s = complex angular frequency, $s = i.\varpi = i.2\pi.f$

S_d = *effective area of drive unit diaphragm* [7], m^2

V_1 = volume of ear in close box [7], m^3

V_1 = volume of ear in box with vent [7], m^3

ρ_0 = density of air (ρ_0= 1.18 kg/m^3) [1], kg/m^3

ϖ = angular frequency $(\varpi = 2.\pi.f)$, rad/s

ϖ_0 = normalized angular frequency, rad/s

$$\left(\omega_0 = \sqrt{\frac{1}{\omega_1.\omega_2}} = \sqrt{\frac{1}{\omega_B.\omega_S}} = \sqrt[4]{\frac{1}{C_{as1}.C_{ab2}.M_{as}.M_{ap2}}} \right)$$

ϖ_s = resonance angular frequency of driver in close box [3], rad/s, $\left(\varpi_S = \sqrt{\frac{1}{C_{as1}.M_{as}}} \right)$

ϖ_B = angular frequency for box 2, rad/s

$$\left(\varpi_B = \sqrt{\frac{1}{C_{ab2}.M_{ap2}}} \right) [4]$$

ϖ_{1or2} = low or high cut of angular frequency, rad/s

Note: In "II. Glossary of symbols" the Thiele-Small loudspeaker parameters [16] presented with *Font style: Italic*.

III. Electrical Characteristics

The analysis of the electrical impedance of the single vented band-pass system of fig. 1 [15] is similar to a vented box system (two maxima and one minimum [11]), see fig. 3.

The input electrical impedance of a loudspeaker in the closed-box is [3]

$$Z_{v1}(\varpi) = R_e + i.\omega.L_e + \frac{(B.l)^2}{R_{ms} + \frac{\frac{1}{C_{ms}} + \frac{S_d^{\,2}}{C_{ab1}}}{i.\omega} + i.\omega.M_{ms}} . \quad (1)$$

The electrical impedance of the vented box is

$$Z_{v2}(\varpi) = \left(\frac{B.l}{S_d}\right)^2 . \left(i.\varpi.C_{ab2} + \frac{1}{R_{aL}} + \frac{1}{i.\varpi.M_{ap2}} \right) . \quad (2)$$

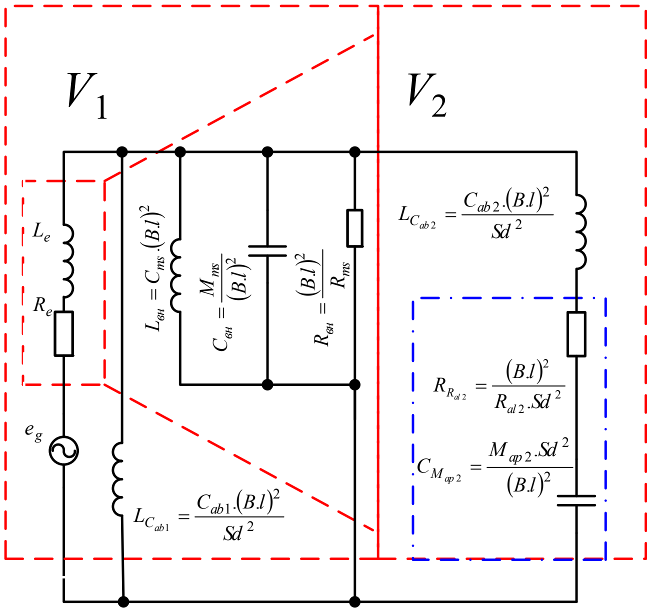

Fig. 2. Simplified electrical equivalent circuit of the double cavity with single vent loudspeaker system [15]

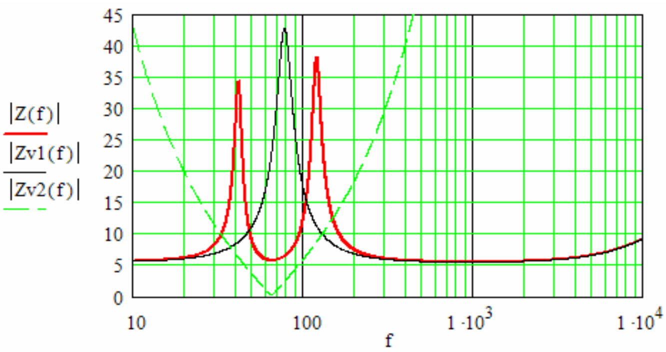

Fig. 3. Magnitude of the Band-pass loudspeaker system impedance

The math expression, Eq. (3), which describes the input electrical impedance, includes the sum of the voice coil electrical impedance $Z_e = R_e + i.\omega.L_e$, the impedance introduced by the mechanical system $Z_{вн}$ and the acoustic volume Z_a (fig.2).

$$Z(\varpi) = R_e + i.\omega.L_e + \frac{(B.l)^2}{R_{ms} + \frac{\frac{1}{C_{ms}} + \frac{S_d^{\,2}}{C_{ab1}}}{i.\omega} + i.\omega.M_{ms} + \frac{S_d^{\,2}}{i.\varpi.C_{ab2} + \frac{1}{R_{aL}} + \frac{1}{i.\varpi.M_{ap2}}}} \quad (3)$$

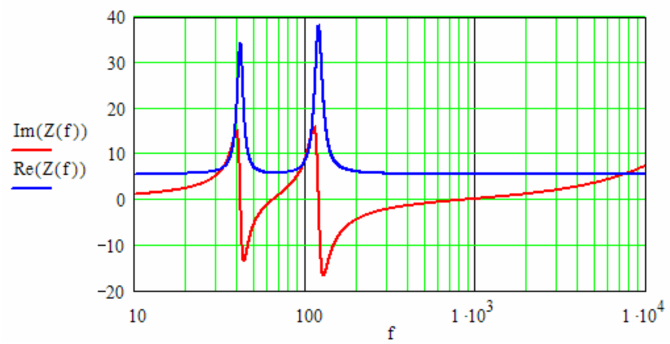

Fig. 4. Real and imaginary part of the Band-pass loudspeaker system impedance

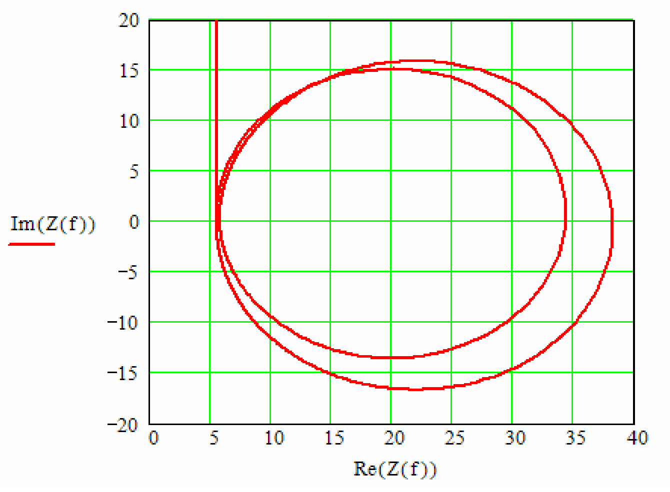

Fig. 5. Complex Impedance (Nyquist plot) of the Band-pass loudspeaker system

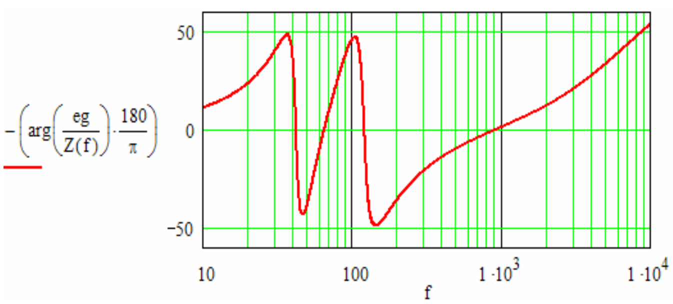

Fig. 6 Phase of the electrical current from the audio amplifier

IV. Acoustical Characteristics

The characteristics of the double cavity with single vent loudspeaker system may be presented with the band-pass system response (transfer) function [13]:

$$K(s)=K_1(s).K_2(s)=\frac{1}{\frac{s^2}{\varpi_1^2}+\frac{s}{\varpi_1.Q_1}+1}\cdot\frac{\frac{s^2}{\varpi_2^2}}{\frac{s^2}{\varpi_2^2}+\frac{s}{\varpi_2.Q_2}+1} \qquad (4)$$

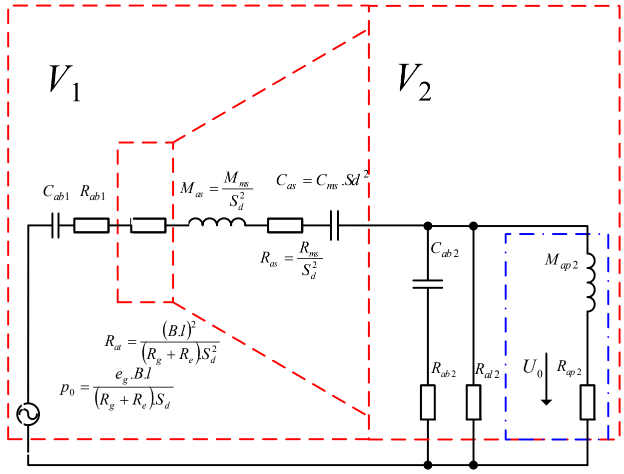

Fig. 7. Simplified acoustical analogous circuit of the double cavity with single vent loudspeaker system [15]

Amplitude – frequency responses are presented in figs. 8÷10.

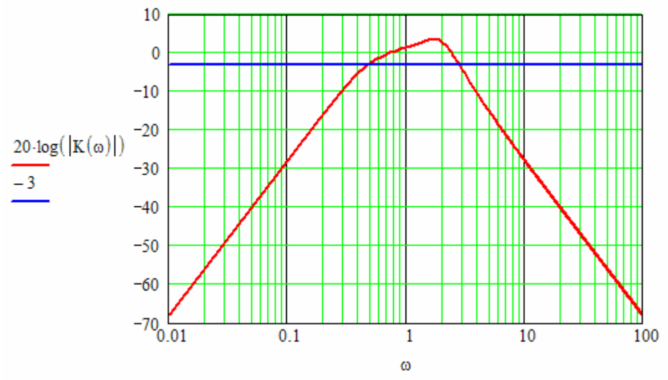

Fig. 8. Normalized amplitude – frequency response of the sound pressure created by the Band-pass loudspeaker system

It is a forth order band-pass filter response (fig. 8) with 12 dB per octave (40 dB per decade) slopes.

The band-pass characteristics will be symmetrical if $\varpi_S=\varpi_B$ [11] and $Q_1=Q_2$.

The phase of the sound pressure created by the Band-pass loudspeaker system $\arg(K(\varpi))$ is plotted in fig. 9.

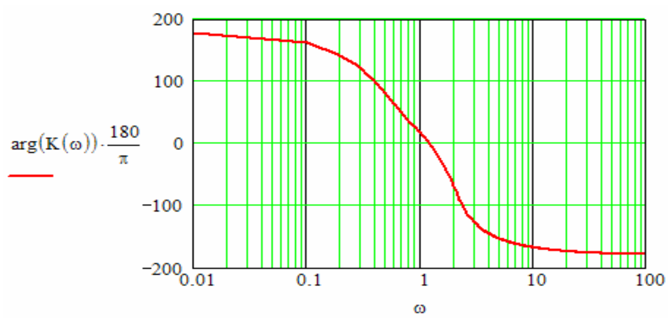

Fig. 9. Normalized frequency response of the phase of the sound pressure created by the Band-pass loudspeaker system

The group time delay $-\frac{d}{d\varpi}\arg(K(\varpi))$ is presented in fig. 10.

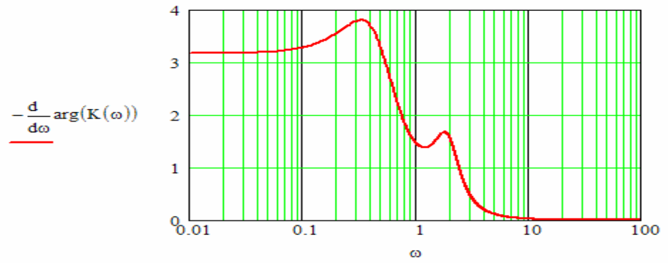

Fig. 10. Normalized frequency response of the group time delay of the sound pressure created by the Band-pass loudspeaker system

For the analysis in the time domain, the impulse response of the loudspeaker $h(t)$ (fig.11) is defined as follows:

$$h(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \dot{K}(j\omega)e^{j\omega t}d\omega \qquad (5)$$

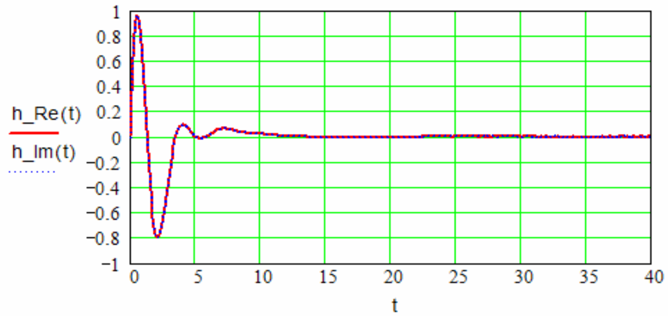

Fig. 11. Normalized impulse response of the sound pressure created by the Band-pass loudspeaker system

The impulse response $h(t)$ is a reaction of $\delta(t)$-Dirac impulse, while the step response $F(t)$ is defined by the integral of $h(t)$:

$$F(t) = \int_{0}^{t} h(t)dt \qquad (6)$$

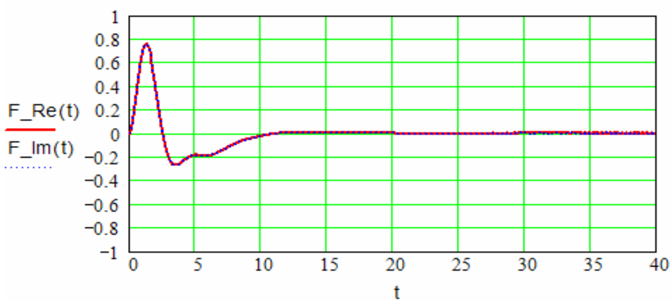

Fig. 12. Normalized step response of the sound pressure created by the Band-pass loudspeaker system

V. Conclusion

The reactance transformation method – Thile-Small [2-4] theory of close and vented system can be applied to the analysis of a band-pass system [5-9, 11, 15].

This work considers researching of the following characteristics of a band-pass loudspeaker system: frequency response of the magnitude (fig. 3), real and imaginer part (fig. 4) of impedance and the complex impedance (fig. 5); electrical phase of the current from audio amplifier (fig. 6); of the amplitude (fig. 8), phase (fig. 9), of the group time delay (fig. 10), impulse (fig. 11) and step (fig. 12), response of the sound pressure created; and in the time domain: impulse (fig. 11) and step (fig. 12) response.

The theoretical analysis of the characteristics and the comparison with the characteristics by computer simulations [15] confirm the proposed ideas.

The results obtained in this paper can be used for theoretical analysis, design and production of band-pass loudspeaker systems.

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