

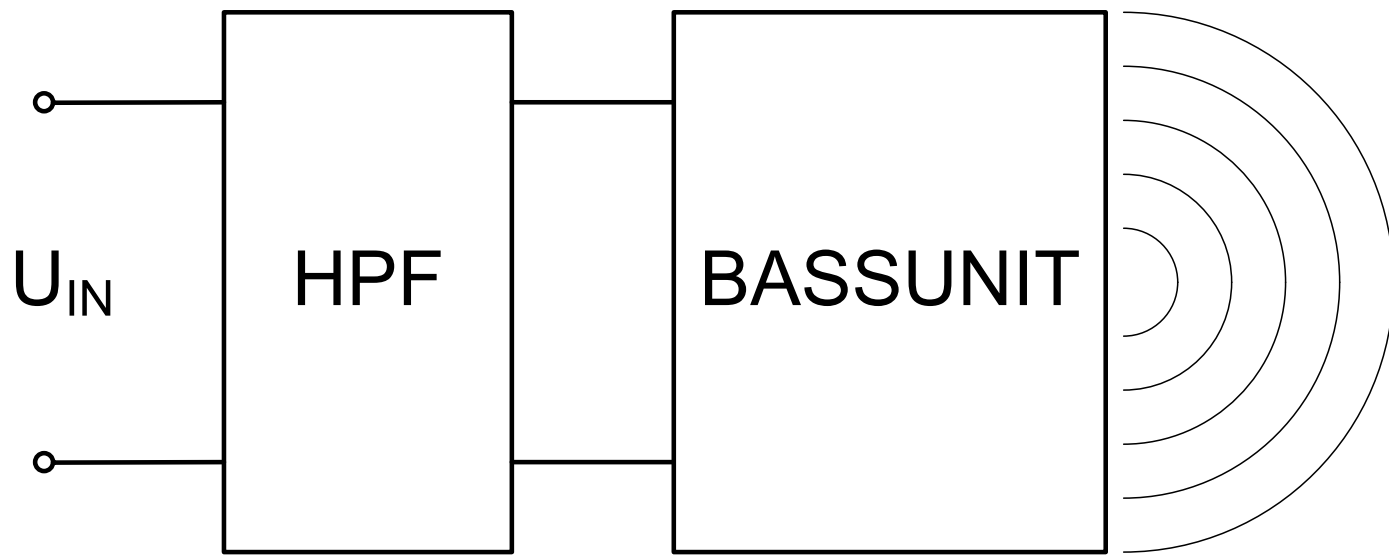


## **Elektroakustika**

# **L11A: Reprodukčtorová sústava s predradeným tvarovacím filtrom**

**doc. Ing. Jozef Juhár, PhD.**

**<http://voice.kemt.fei.tuke.sk>**



# Prenosová funkcia predradeného filtra

$$H_{HPF}(s) = \frac{s_e^2}{s_e^2 + a_1 s_e + 1} = \frac{s_e^2}{s_e^2 + s_e/Q_e + 1}$$

$$s_e = \frac{s}{\omega_e}$$

$$a_1 = \frac{1}{Q_e}$$

# Prenosová funkcia reproduktora v zatvorenej ozvučnici

$$G_{CB}(s) = \frac{s_C^2}{s_C^2 + a_1 s_C + 1} = \frac{s_C^2}{s_C^2 + s_C / Q_{TC} + 1}$$

$$s_C = \frac{s}{\omega_C}$$

$$a_1 = \frac{1}{Q_{TC}}$$

# Prenosová funkcia reproduktora v zatvorenej ozvučnici s predradeným filtrom

$$H_{CB}(s) = H_{HPF}(s) \cdot G_{CB}(s) = \frac{s_e^2}{s_e^2 + s_e/Q_e + 1} \frac{s_C^2}{s_C^2 + s_C/Q_{TC} + 1}$$

$$s_e = \frac{s}{\omega_e} \quad s_C = \frac{s}{\omega_C}$$

# BassUnit - Dialog

Definition Def\_BassUnit / Calculator X

<b>Resonance frequency</b> fs... <input type="text" value="25Hz"/> ...Hz...	<b>Electrical quality</b> Qes... <input type="text" value="0.3"/>	<b>Mechanical quality</b> Qms... <input type="text" value="3.99"/>	<b>Voice coil resistance</b> Re... <input type="text" value="6.1ohm"/> ..ohm..	<b>Voice coil inductance</b> Le... <input type="text" value="3.08mH"/> H... ExpoLe=0.618	<b>Equ. vol. to compliance</b> Vas... <input type="text" value="164L"/> m3,..in3	<b>Diaphragm dimension</b> SD... <input type="text" value="350cm2"/> m2,..in2 Cone
--	---	--	---	--	---	--

<b>Excursion max.</b> Xms <input type="text" value="4mm"/> m,..in	<b>Generator resistance</b> Rg <input type="text"/>	<b>Mass-load factor</b> mb <input type="text" value="1"/> 0.95...1	<b>Enclosure volume</b> Vb <input type="text" value="53.18L"/> m3,..in3,L	<b>Quality factor/frequency</b> Qb/fo <input type="text" value="1000"/>	<input type="checkbox"/> <b>Vented</b>	<b>Helmholtz resonance</b> fb... <input type="text"/> ..Hz..
--	---	---	--	---	--	---

**Closed Box System**

fc	Qtc	Directivity frequ. fD	f3
<input type="text" value="50.521Hz"/>	<input type="text" value="0.564"/>	<input type="text" value="518Hz"/>	<input type="text" value="42Hz"/>

Lw max. 4-pi-sr	Pel max.	Uo max. rms	Reverb. -60dB	Ripple
<input type="text" value="96.11dB"/>	<input type="text" value="6.03W"/>	<input type="text" value="6.06V"/>	<input type="text" value="85.7ms"/>	<input type="text" value="2.58m dB"/>

**HP-Filter** on/off  
 Quality factor   
 Pole - frequency   
 ..Hz..

**Identification**

**Alignments...**
 **Diagram...**
 **Evaluate**
 **From script**
 **Copy to clipboard and close**

## BassUnit – Dialog/Alignments: Výber realizácie reproduktora v zatvorenej ozvučnici s predradeným filtrom

### Closed Cabinet Alignments

Alignment table fsb: 25Hz      Qtsbg: 0.279      Qb/fo: 1000      CHI 4 k = 0.795

Qtc	fc [Hz]	Vb [L]	f3 [Hz]	Lwmax [dB]	Qe	fe [Hz]	t60 [ms]	Ripple [dB]
0.823	73.7	21.3	35	91	3.843	38.1	242	1.26
0.721	64.6	28.9	34	91.2	3.069	36.6	200	0.59
0.648	58.1	37.3	35	92.2	2.457	37	157	0.21
0.598	53.6	45.6	37	93.9	1.976	39.1	118	0.05
0.564	50.5	53.2	42	96.1	1.599	43	86	
0.541	48.5	59.4	48	98.8	1.307	48.5	61	
0.541	48.5	59.4	48	98.8	1.307	48.5	61	
0.539	48.3	60	50	99.2	1.225	47.7	55	

Query (Select only alignments with...)

Enclosure volume	HP-filter quality factor	Cut-off frequency	Max. SPL 1m, 4-pi-sr	Enclosure quality/ fb
<u>V</u> b	<u>Q</u> e	<u>f</u> 3	<u>S</u> PLmax	<u>Q</u> b/fo
< <input type="text"/>	< <input type="text"/>	<50.0Hz <input type="text"/>	< <input type="text"/>	<input type="text"/>
m3,...,in3,L		..Hz..	dB	

Alignment list       Diagram       Copy alignment to Def\_BassUnit Calculator

Lw in a 4-pi-sr. room

Alignment family

- Quasi-Butterworth
- Chebyshev
- Butterworth-Thomson
  
- High-pass filtered

# Skript

| Seas Prestige CA26RE4X H1316  
|  $Revc=6.1\Omega$ ;  $Levc=3.08mH$ ;  $Bl=11.6N/A$ ;  $Mmd=38.5g$ ;  $Mmrd=3.8g$ ;  
|  $Rms=1.66Ns/m$ ;  $Cms=1.1mm/N$ ;  $Sd=350cm^2$   
|  $Fs=25Hz$ ;  $Qts=0.28$ ;  $Qms=3.99$ ;  $Qes=0.30$ ;  $Vas=164lit.$ ,  
|  $y_{max}=4mm$ ;  $sens=91dB$ ;  $Pe(lt)=80W$

Def\_BassUnit 'BU2'

$SD=350cm^2$   $dD1=5.5cm$   $tD1=6.5cm$  |Cone

$fs=25Hz$   $Vas=164L$   $Qms=3.99$

$Qes=0.3$   $Re=6.1\Omega$   $Le=3.08mH$   $ExpoLe=0.618$

$Xms=4mm$

$Vb=53.18L$

$Qe=1.599$   $fe=43.0Hz$

|Performance in sealed enclosure:

|  $f_c$   $Q_{tc}$   $f_D$   $f_3$

| 50.5Hz 0.564 517.6Hz 41.8Hz

|  $Lw_{max}$   $P_{elmax}$   $U_{oRms}$   $t_{60}$  Ripple

| 96.1dB 6.0W 6.06V 85.7ms 2.6mdB

System 'L2'

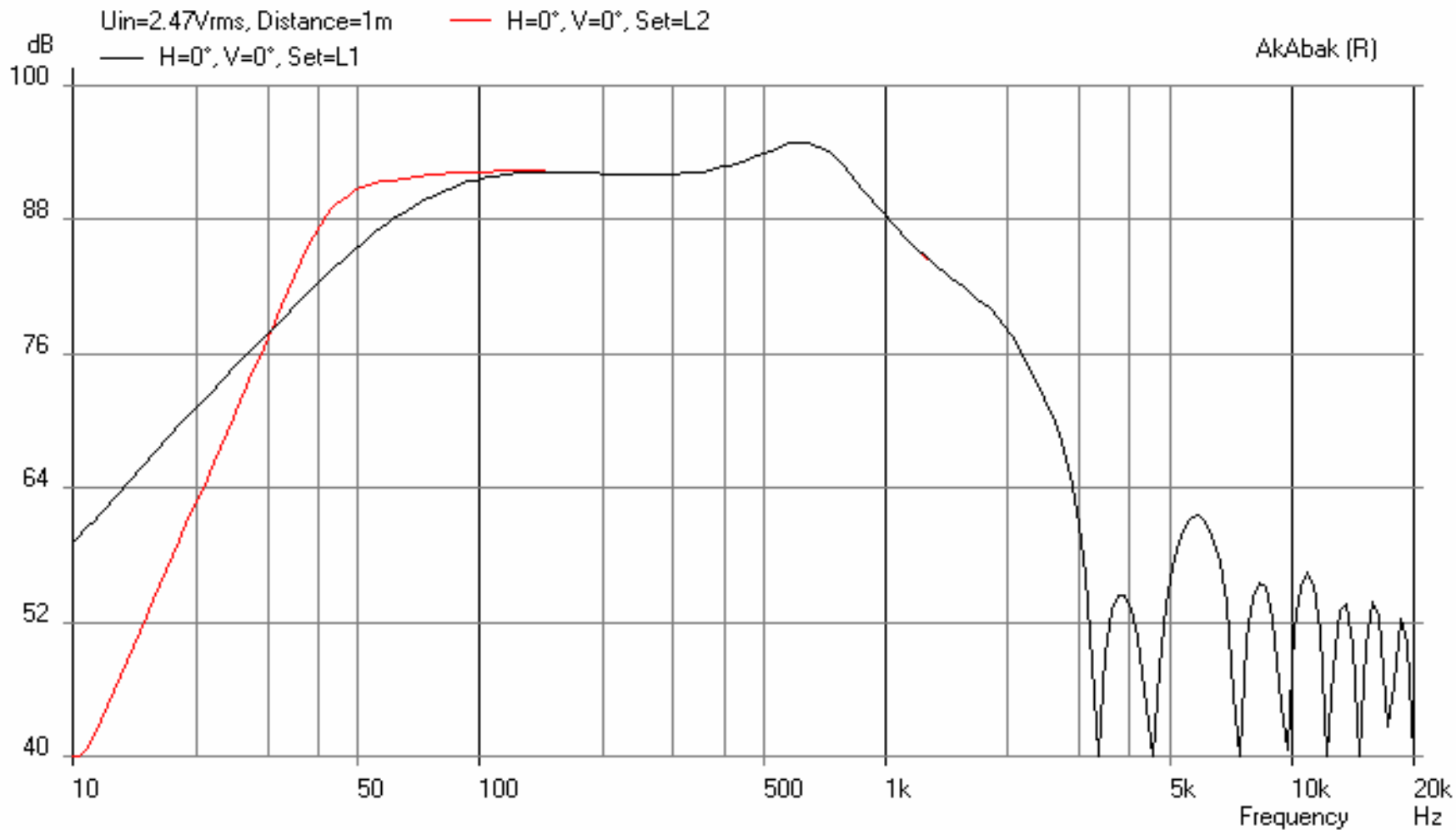
BassUnit 'B2' Def='BU2' Node=1=0

$x=0$   $y=0$   $z=0$   $HAngle=0$   $VAngle=0$



# AFCH charakteristiky - porovnanie

## 9. Sound Pressure of L11A, Lp (Phase)



# Skript: BassUnit+Filter

| Seas Prestige CA26RE4X H1316  
| Revc=6.1Ohms; Lev=3.08mH; Bl=11.6N/A; Mmd=38.5g;  
| Mmrd=3.8g; Rms=1.66Ns/m; Cms=1.1mm/N; Sd=350cm2  
| Fs=25Hz; Qts=0.28; Qms=3.99; Qes=0.30; Vas=164lit.,  
| ymax=4mm; sens=91dB; Pe(lt)=80W

Def\_BassUnit 'BU2'

SD=350cm2 dD1=5.5cm tD1=6.5cm |Cone

fs=25Hz Vas=164L Qms=3.99

Qes=0.3 Re=6.1ohm Le=3.08mH ExpoLe=0.618

Xms=4mm

Vb=53.18L

**Qe=1.599 fe=43.0Hz**

|Performance in sealed enclosure:

| fc Qtc fD f3

| 50.5Hz 0.564 517.6Hz 41.8Hz

| Lwmax Pelmax UoRms t60 Ripple

| 96.1dB 6.0W 6.06V 85.7ms2.6mdB

System 'L3'

Filter 'HPF1'

**fo=43Hz** vo=1

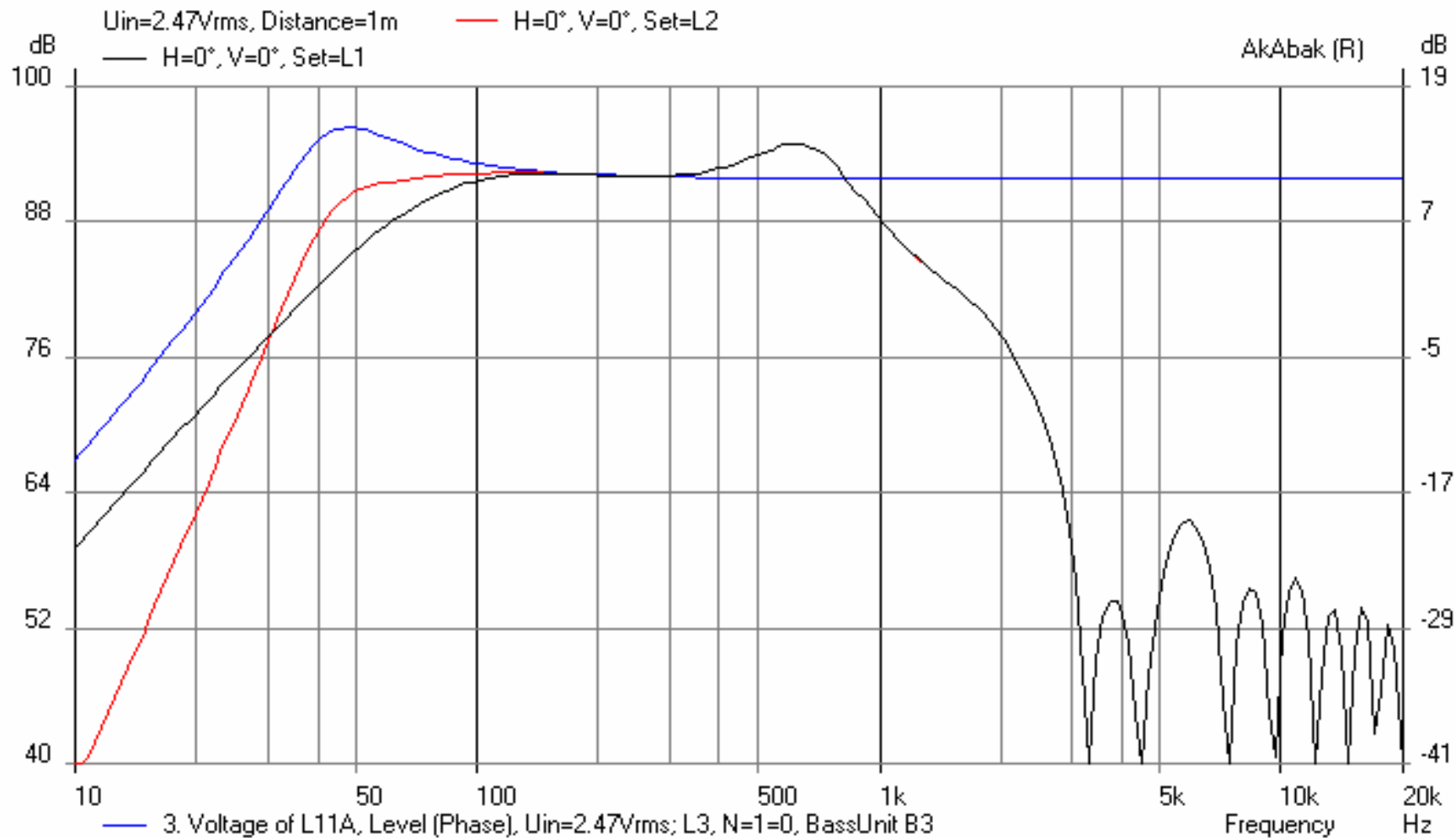
{b2=1;

a2=1; **a1=0.625**; a0=1; }

BassUnit 'B3' Def='BU2' Node=1=0

x=0 y=0 z=0 HAngle=0 VAngle=0

### 9. Sound Pressure of L11A, Lp (Phase)



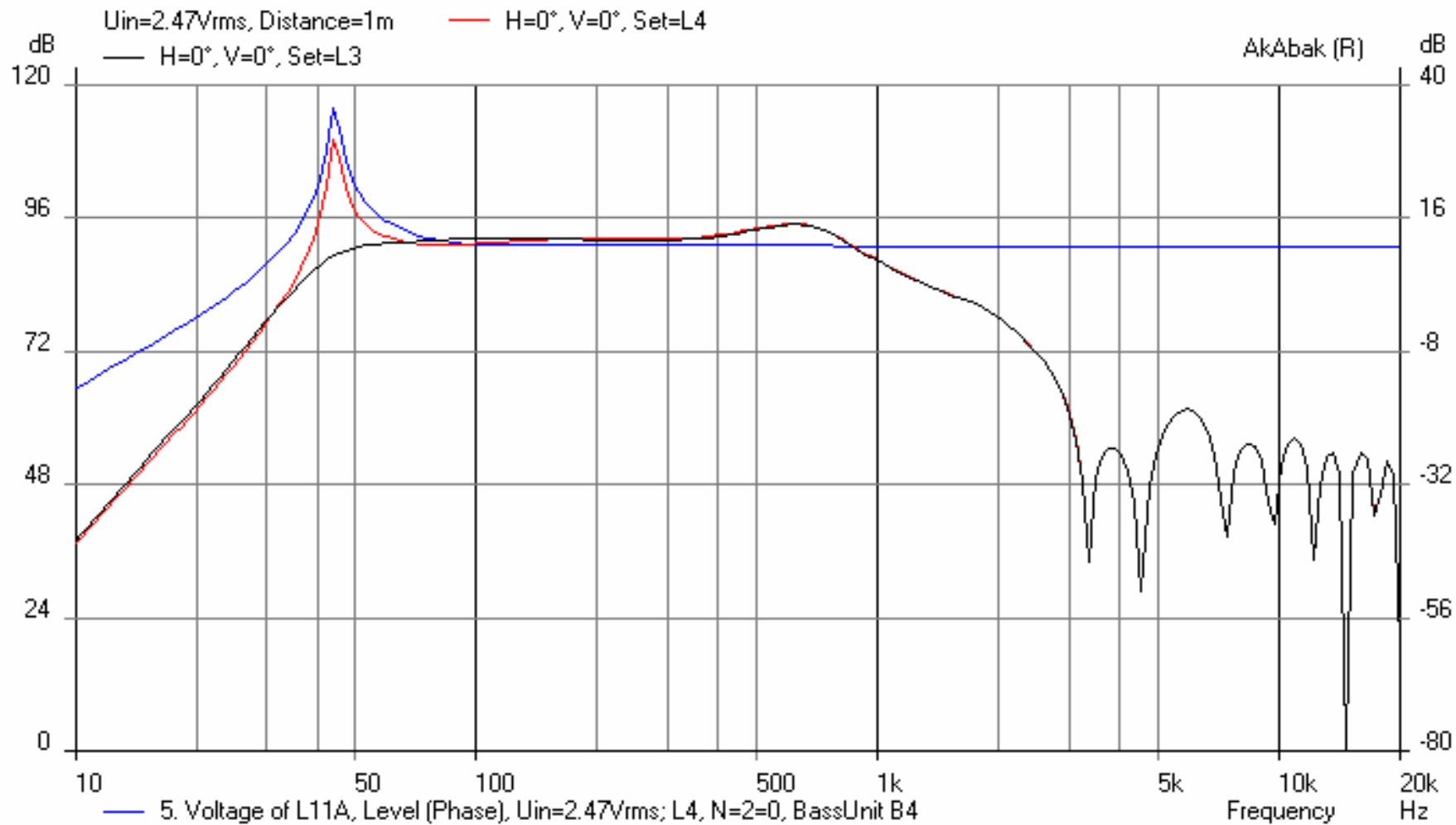
# Skript: BassUnit+LCR Filter

Def\_BassUnit 'BU2'  
SD=350cm<sup>2</sup> dD1=5.5cm tD1=6.5cm |Cone  
fs=25Hz Vas=164L Qms=3.99  
Qes=0.3 Re=6.1ohm Le=3.08mH ExpoLe=0.618  
Xms=4mm  
Vb=53.18L  
|Qe=1.599 fe=43.0Hz  
|Performance in sealed enclosure:  
| fc Qtc fD f3  
| 50.5Hz 0.564 517.6Hz 41.8Hz  
| Lwmax Pelmax UoRms t60 Ripple  
| 96.1dB 6.0W 6.06V 85.7ms2.6m dB

System 'L4'  
Capacitor Node=1=2 C=0.971mF  
Coil Node=2=0 L=14.111mH  
SynthesisInfo  
Passive FirstNode=1 RL=6.1ohm QL=0  
fo=43Hz vo=1  
{b2=1;  
a2=1; a1=0.625; a0=1; }

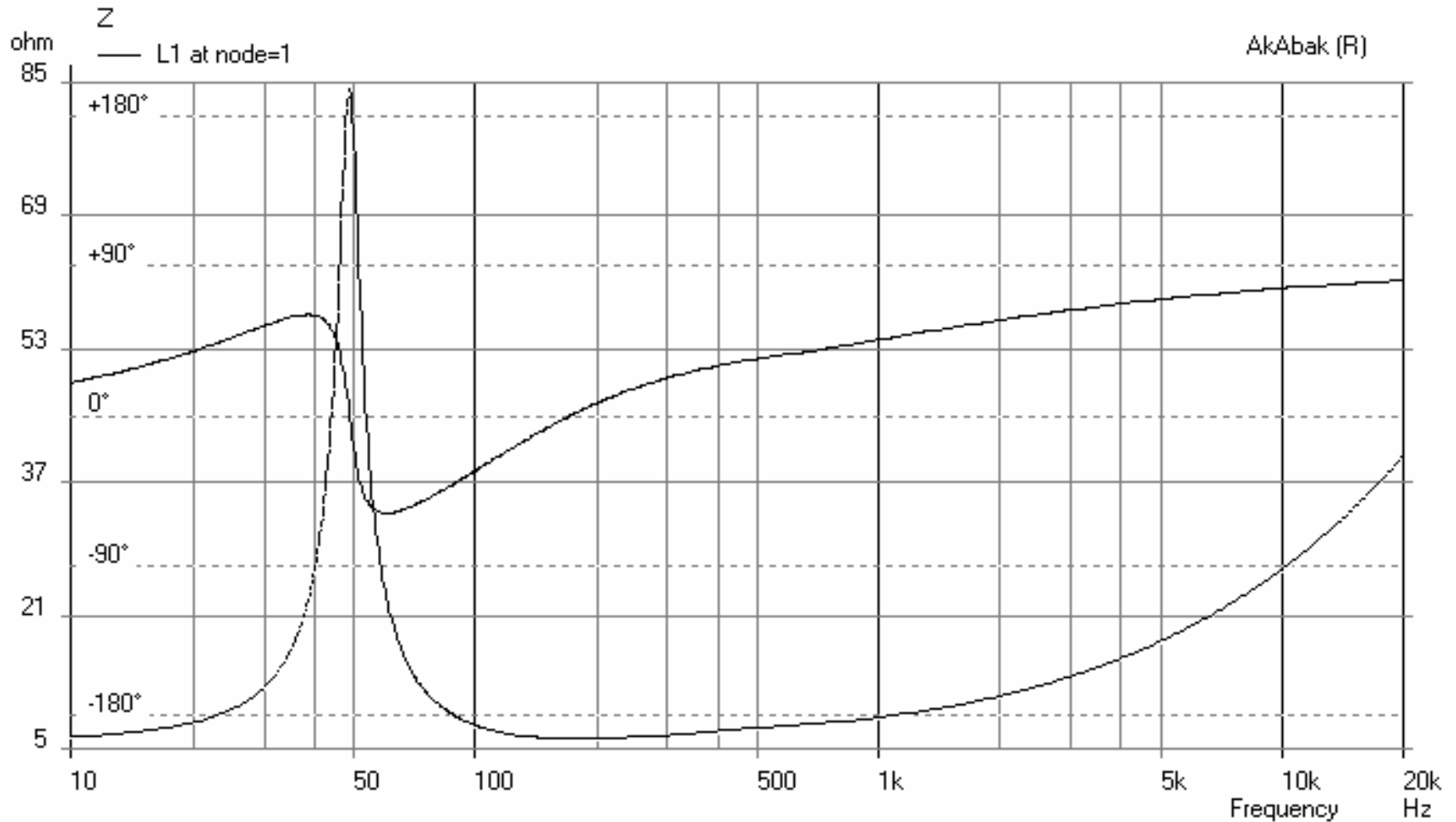
BassUnit 'B4' Def='BU2' Node=2=0  
x=0 y=0 z=0 HAngle=0 VAngle=0

#### 4. Sound Pressure of L11A, Lp (Phase)



# Impedancia reproduktora v zatvorenej ozvučnici

6. Impedance of L11A, Amplitude (Phase)



# Tools/Impedance Compensation

## Dyn. Driver Impedance Compensation

Resonance frequ.

$f_s$

43.97Hz ..Hz..

Target resistance

RL  
6.1 ..ohm..

Equalize at resonance

Opt.=5.29, 5.314

Equ. at high frequency

Lm

14.827mH

Cm

0.884mF

Rm

1ohm

Re

..ohm..

Ce

F..

Fix Lm and Cm

Fix Rm

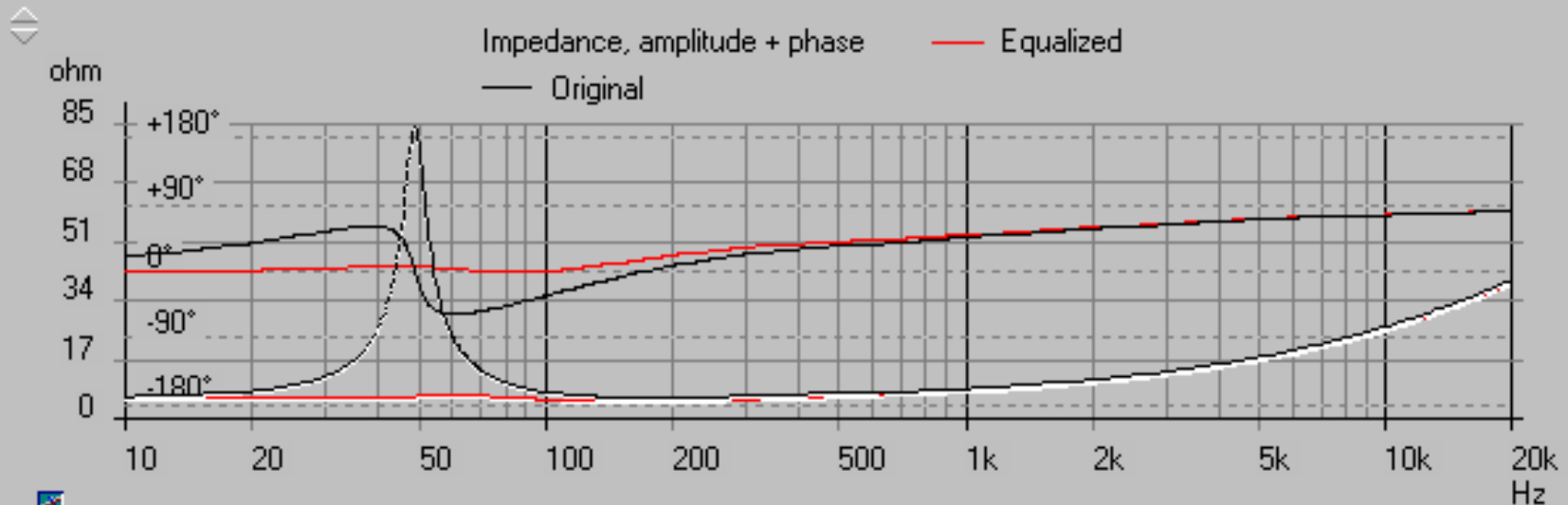
Fix Re and Ce

Get impedance curves...

Estimate

Optimize

Copy and close



## Skript: Impedance compensation

Def\_BassUnit 'BU2'

SD=350cm<sup>2</sup> dD1=5.5cm tD1=6.5cm |Cone

fs=25Hz Vas=164L Qms=3.99

Qes=0.3 Re=6.1ohm Le=3.08mH ExpoLe=0.618

Xms=4mm

Vb=53.18L

|Qe=1.599 fe=43.0Hz

|Performance in sealed enclosure:

| fc Qtc fD f3

| 50.5Hz 0.564 517.6Hz 41.8Hz

| Lwmax Pelmax UoRms t60 Ripple

| 96.1dB 6.0W 6.06V 85.7ms 2.6m dB

System 'L4'

Capacitor Node=1=2 C=0.971mF

Coil Node=2=0 L=14.111mH

SynthesisInfo

Passive FirstNode=1 RL=6.1ohm QL=0

fo=43Hz vo=1

{b2=1;

a2=1; a1=0.625; a0=1; }

|Impedance compensation

Capacitor Node=2=0 C=0.884mF Rs=7.1ohm Ls=14.82mH

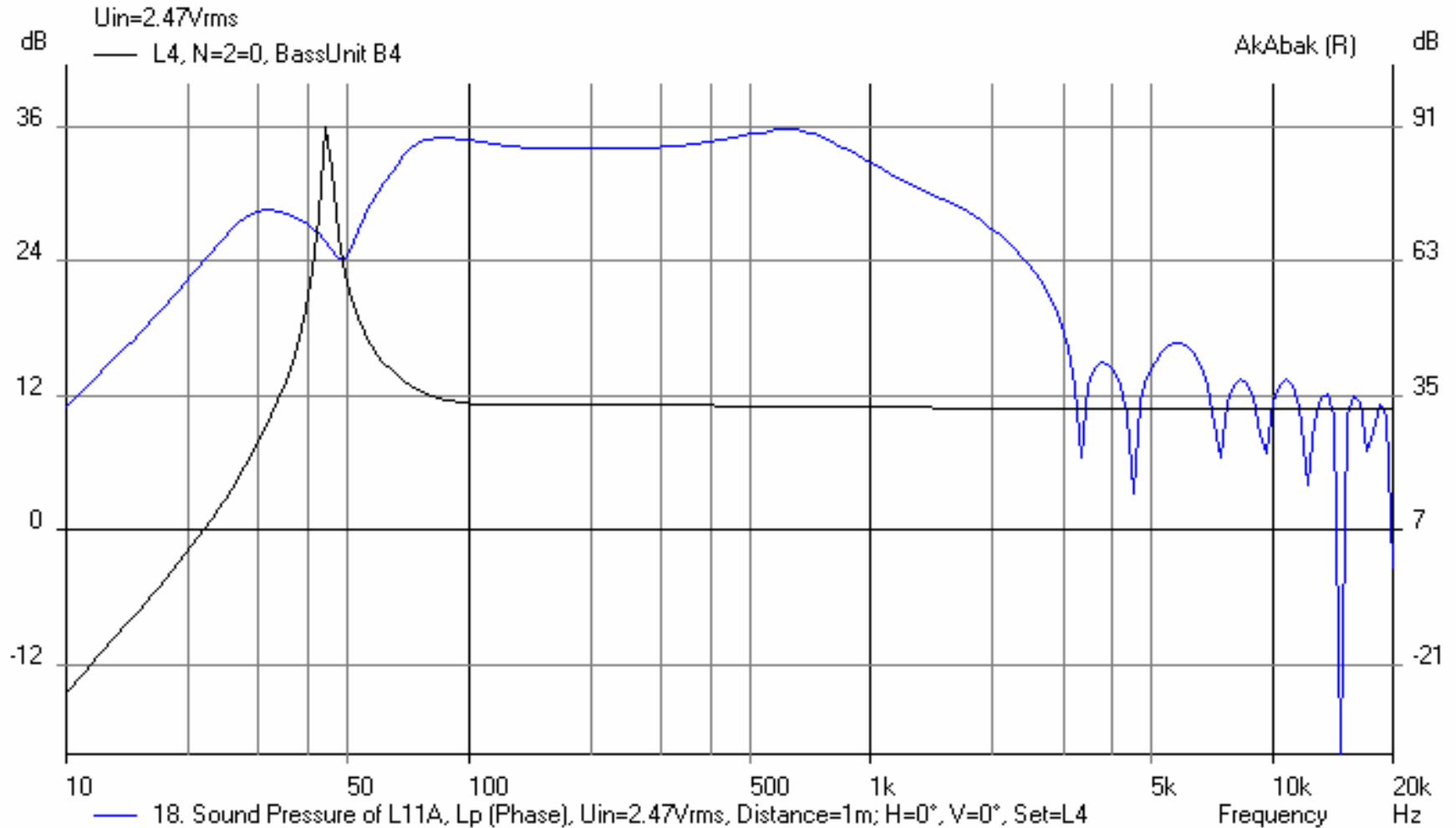
BassUnit 'B4' Def='BU2' Node=2=0

x=0 y=0 z=0 HAngle=0 VAngle=0



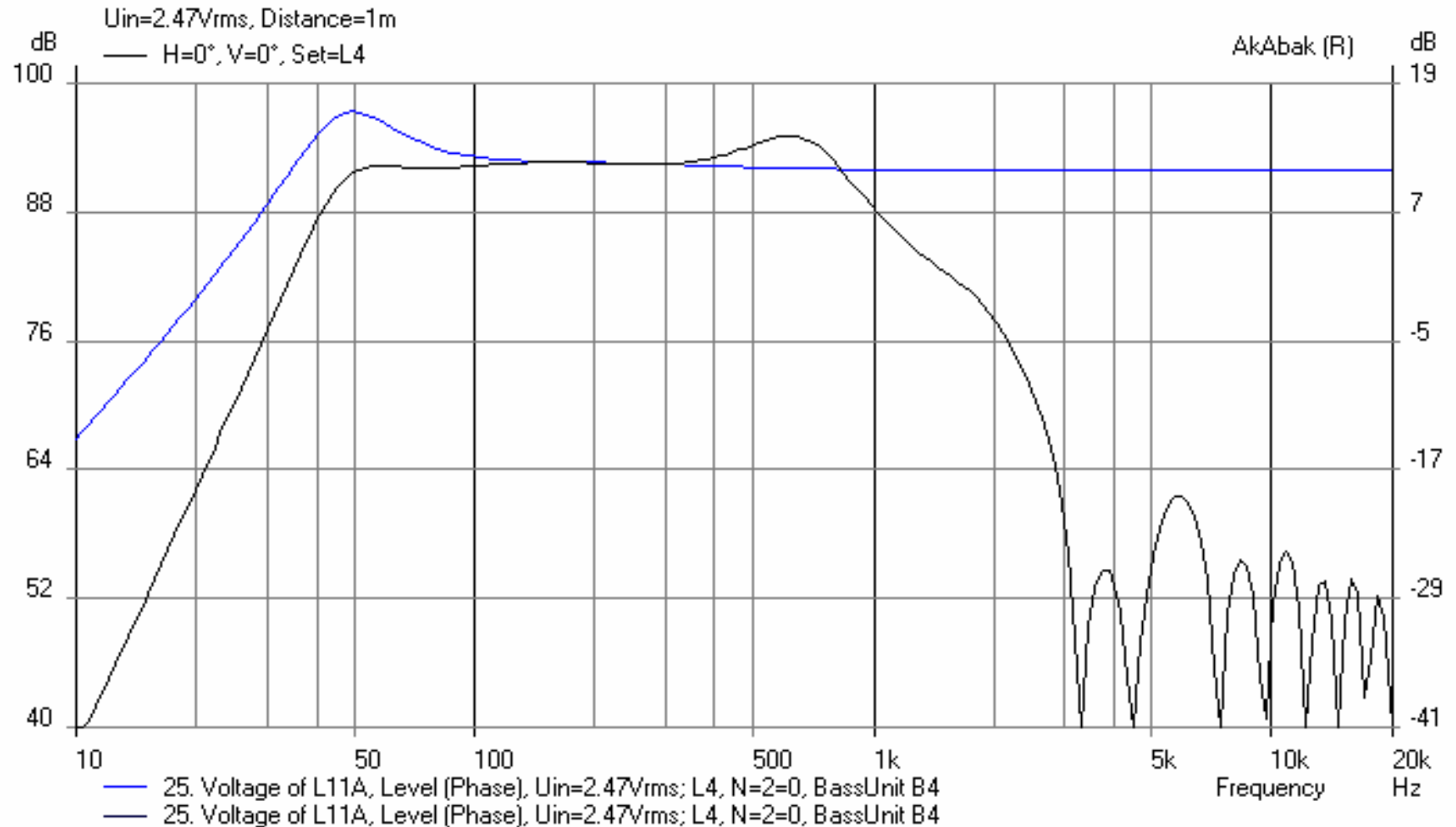
# Ak je kompenzačný obvod naladený na frekvenciu impedancie

5. Voltage of L11A, Level (Phase)



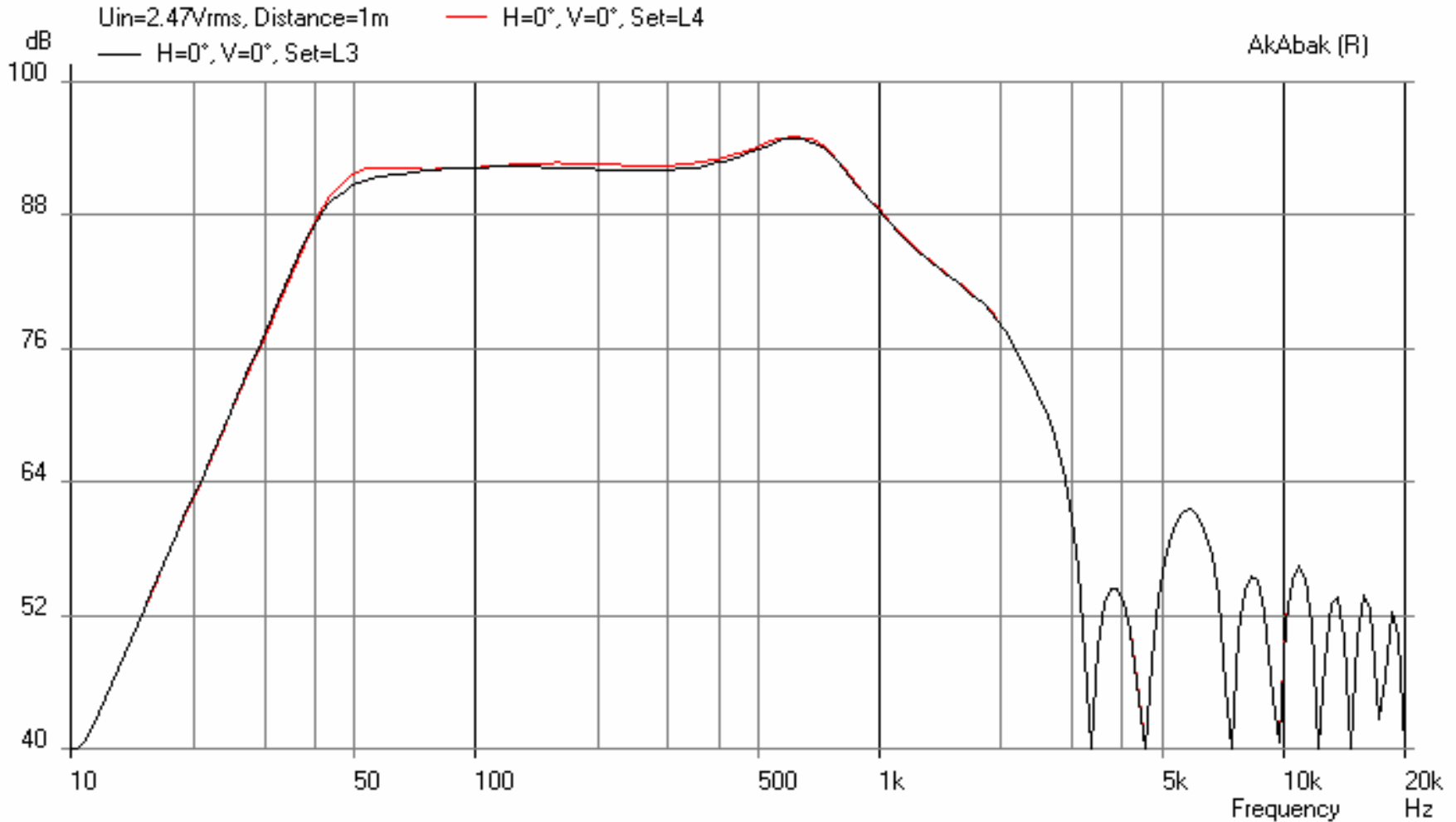
# Ak je kompenzačný obvod naladený na frekvenciu predradeného filtra

23. Sound Pressure of L11A, Lp (Phase)

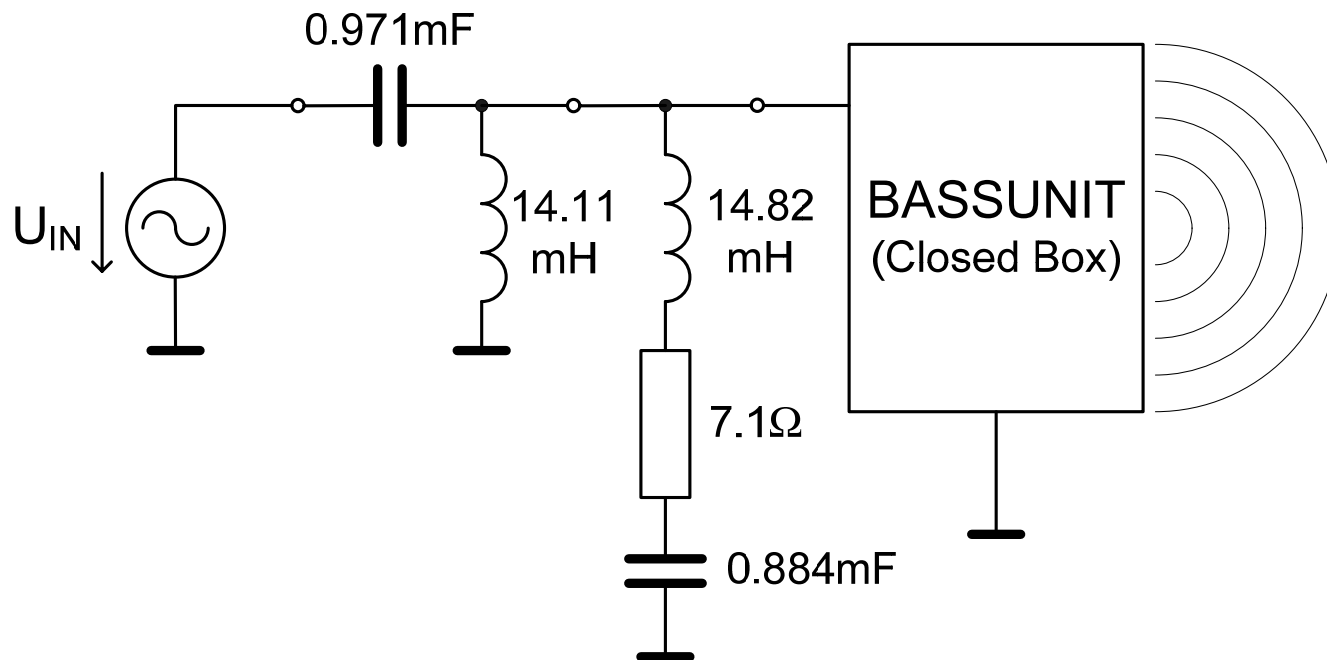


# Ideálny versus reálny filter s kompenzačným obvodom: porovnanie

26. Sound Pressure of L11A, Lp (Phase)



# Schématické zapojenie tvarovacieho filtra s kompenzačným obvodom pre reproduktor v zatvorenej ozvučnici



# Prenosová funkcia reproduktora v basreflexovej ozvučnici

$$G_{VB}(s) = \frac{s_0^4}{s_0^4 + a_1 s_0^3 + a_2 s_0^2 + a_3 s_0 + 1} \quad s_0 = \frac{s}{\omega_0}$$

$$a_1 = \frac{Q_L + h \cdot Q_T}{\sqrt{h} \cdot Q_L \cdot Q_T} \quad \omega_0 = \sqrt{\omega_B \omega_S}$$

$$a_2 = \frac{h + (\alpha + 1 + h^2) \cdot Q_L \cdot Q_T}{\sqrt{h} \cdot Q_L \cdot Q_T}$$

$$a_3 = \frac{h \cdot Q_L + Q_T}{\sqrt{h} \cdot Q_L \cdot Q_T}$$

# Prenosová funkcia sústavy s basreflexovou ozvučnicou a predradeným filtrom: hornopriepustný filter 6. rádu

$$H_{BP6}(s) = H_{HPF}(s)G_{VB}(s) = \frac{s_e^2}{s_e^2 + s_e/Q_e + 1} \frac{s_0^4}{s_0^4 + a_1s_0^3 + a_2s_0^2 + a_3s_0 + 1}$$

$$H_{BP6}(s) = \frac{c_6s_1^6}{d_6s_1^6 + d_5s_1^5 + d_4s_1^4 + d_3s_1^3 + d_2s_1^2 + d_1s_1 + 1}$$

$$s_1 = \frac{s}{\omega_1}$$

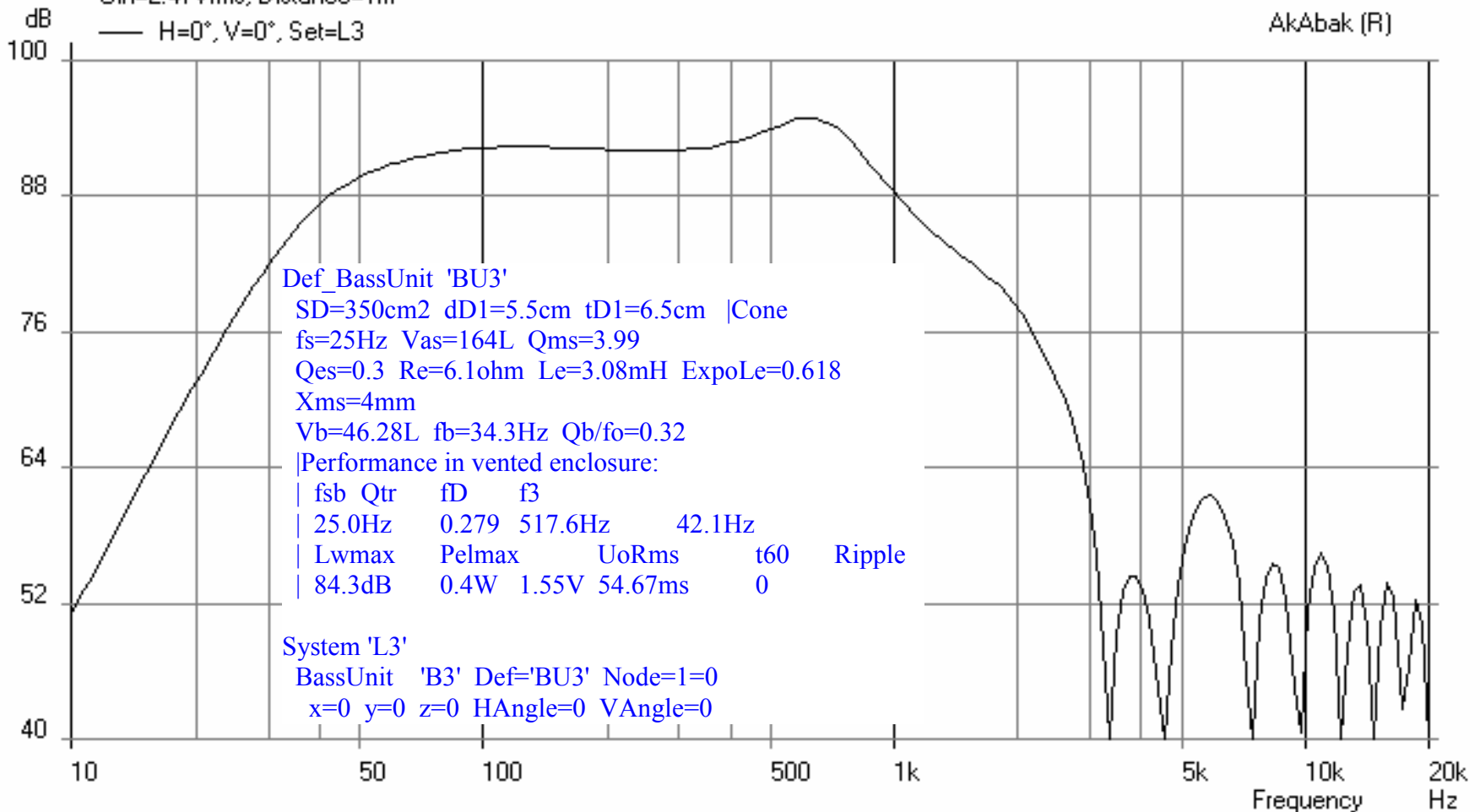
# Sústava s basreflexovou ozvučnicou bez predradeného filtra

3. Sound Pressure of L11B, Lp (Phase)

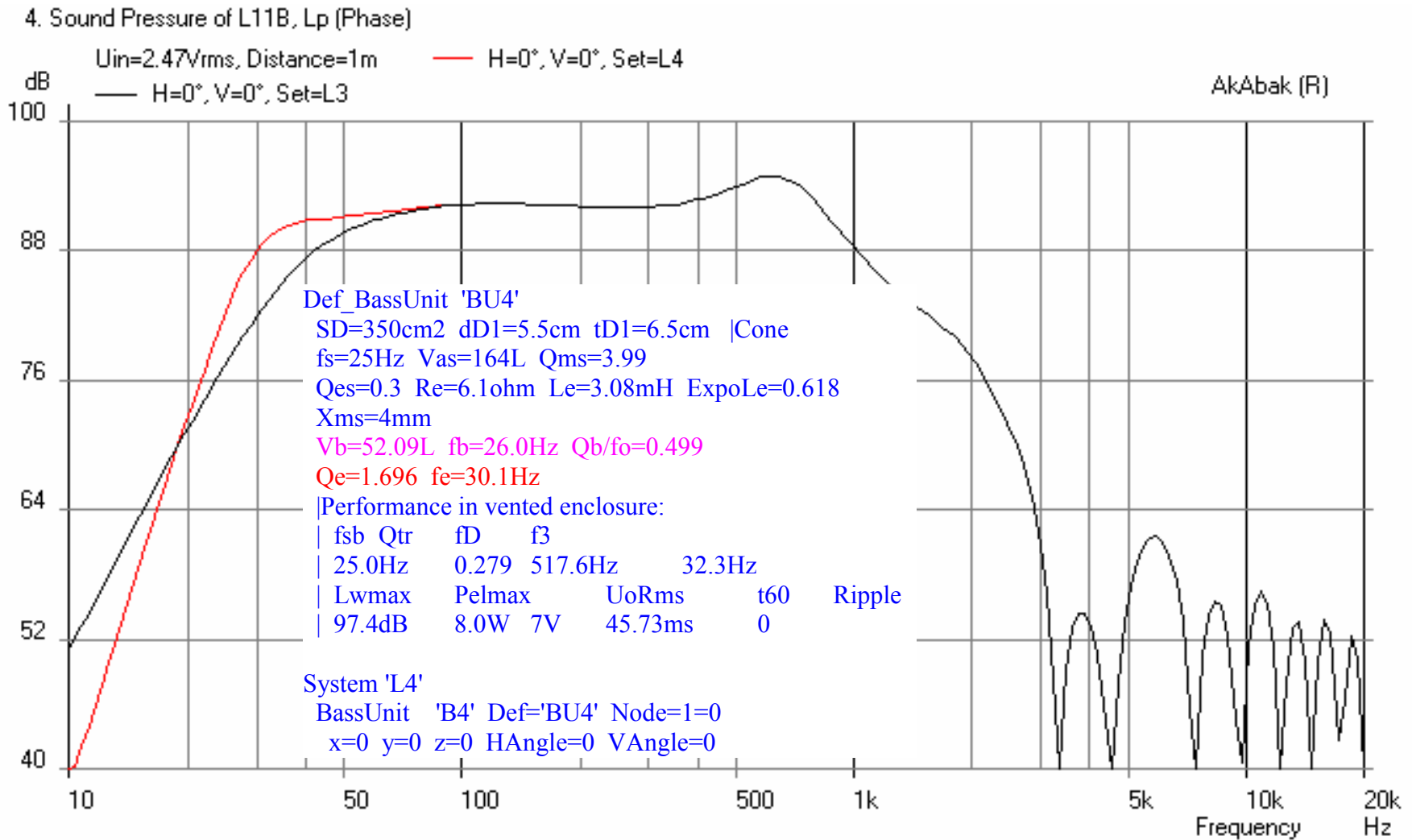
Uin=2.47Vrms, Distance=1m

— H=0°, V=0°, Set=L3

AkAbak (R)



# Sústava s basreflexovou ozvučnicou a tvarovacím filtrom (v definičnej časti skriptu)





# Sústava s basreflexovou ozvučnicou a tvarovacím filtrom (samostatný filter v hlavnej časti skriptu)

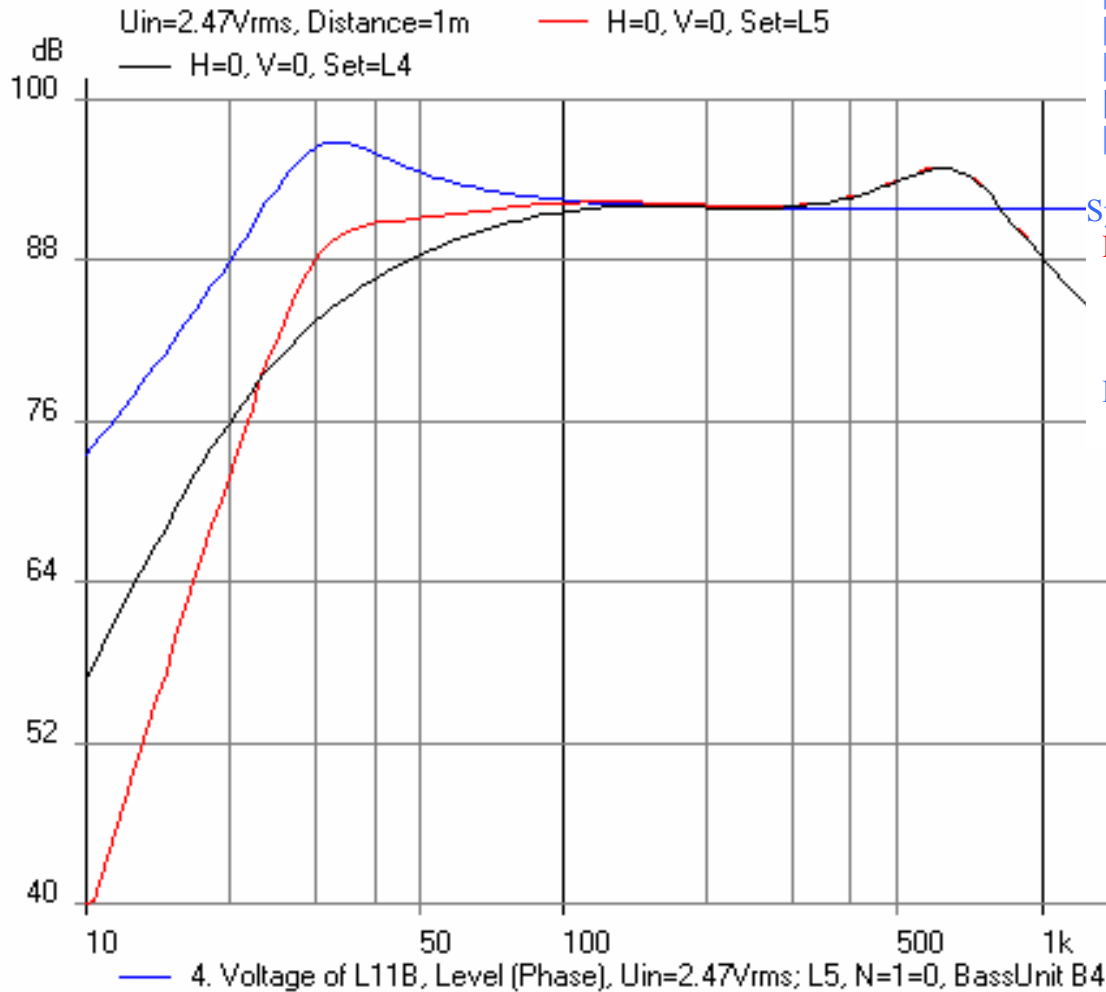
Def\_BassUnit 'BU4'  
 SD=350cm2 dD1=5.5cm tD1=6.5cm |Cone  
 fs=25Hz Vas=164L Qms=3.99  
 Qes=0.3 Re=6.1ohm Le=3.08mH ExpoLe=0.618  
 Xms=4mm  
 Vb=52.09L fb=26.0Hz Qb/fo=0.499

|Qe=1.696 fe=30.1Hz

|Performance in vented enclosure:

fsb	Qtr	fD	f3	Lwmax	Pelmax	UoRms	t60	Ripple
25.0Hz	0.279	517.6Hz	32.3Hz	97.4dB	8.0W	7V	45.73ms	0

## 3. Sound Pressure of L11B, Lp (Phase)



System 'L5'

Filter 'hp2'

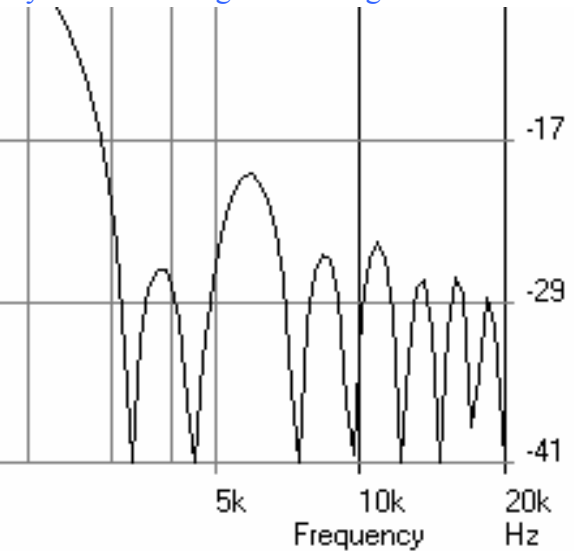
fo=30.1Hz vo=1

{b2=1;

a2=1; a1=0.5896; a0=1; }

BassUnit 'B4' Def='BU4' Node=1=0

x=0 y=0 z=0 HAngle=0 VAngle=0

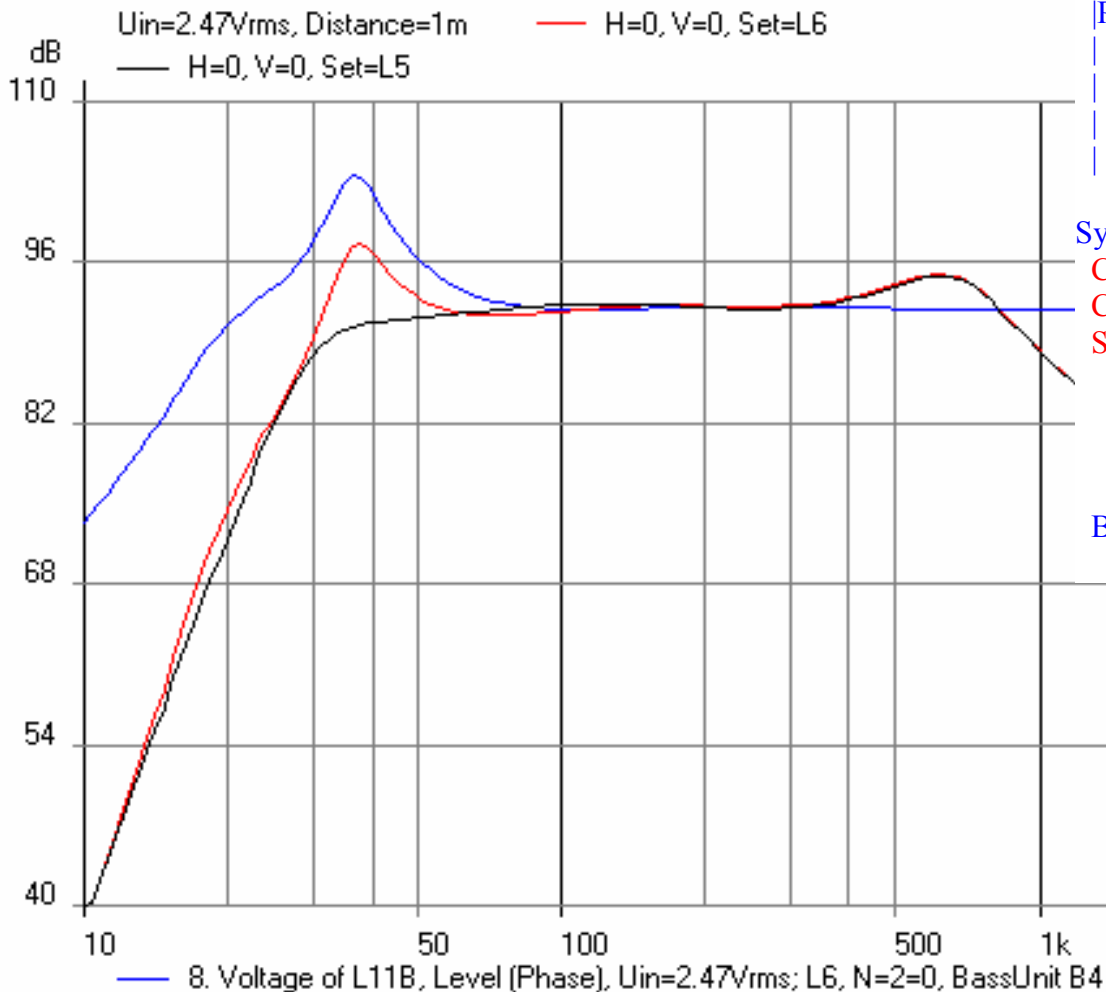


# Sústava s basreflexovou ozvučnicou a tvarovacím filtrom (samostatný filter v hlavnej časti skriptu vo forme obvodovej realizácie)

Def\_BassUnit 'BU4'  
 SD=350cm<sup>2</sup> dD1=5.5cm tD1=6.5cm |Cone  
 fs=25Hz Vas=164L Qms=3.99  
 Qes=0.3 Re=6.1ohm Le=3.08mH ExpoLe=0.618  
 Xms=4mm  
 Vb=52.09L fb=26.0Hz Qb/fo=0.499

|Qe=1.696 fe=30.1Hz  
 Performance in vented enclosure:  
 | fsb Qtr fD f3  
 | 25.0Hz 0.279 517.6Hz 32.3Hz  
 | Lwmax Pelmax UoRms t60 Ripple  
 | 97.4dB 8.0W 7V 45.73ms 0

## 7. Sound Pressure of L11B, Lp (Phase)



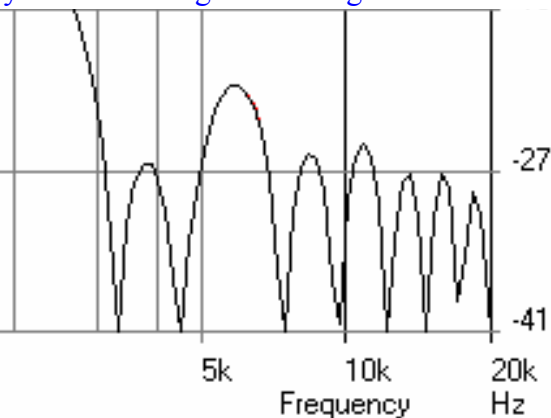
## System 'L6'

Capacitor Node=1=2 C=1.47mF  
 Coil Node=2=0 L=19.017mH

## SynthesisInfo

Passive FirstNode=1 RL=6.1ohm QL=0  
 fo=30.1Hz vo=1  
 {b2=1;  
 a2=1; a1=0.5896; a0=1; }

BassUnit 'B4' Def='BU4' Node=2=0  
 x=0 y=0 z=0 HAngle=0 VAngle=0



# Impedanční křivka

Def\_BassUnit 'BU2'

SD=350cm2 dD1=5.5cm tD1=6.5cm |Cone

fs=25Hz Vas=164L Qms=3.99

Qes=0.3 Re=6.1ohm Le=3.08mH ExpoLe=0.618

Xms=4mm

Vb=147L

|Performance in sealed enclosure:

| fc Qtc fD f3

| 36.4Hz 0.406 517.6Hz 75.4Hz

| Lwmax Pelmax UoRms t60 Ripple

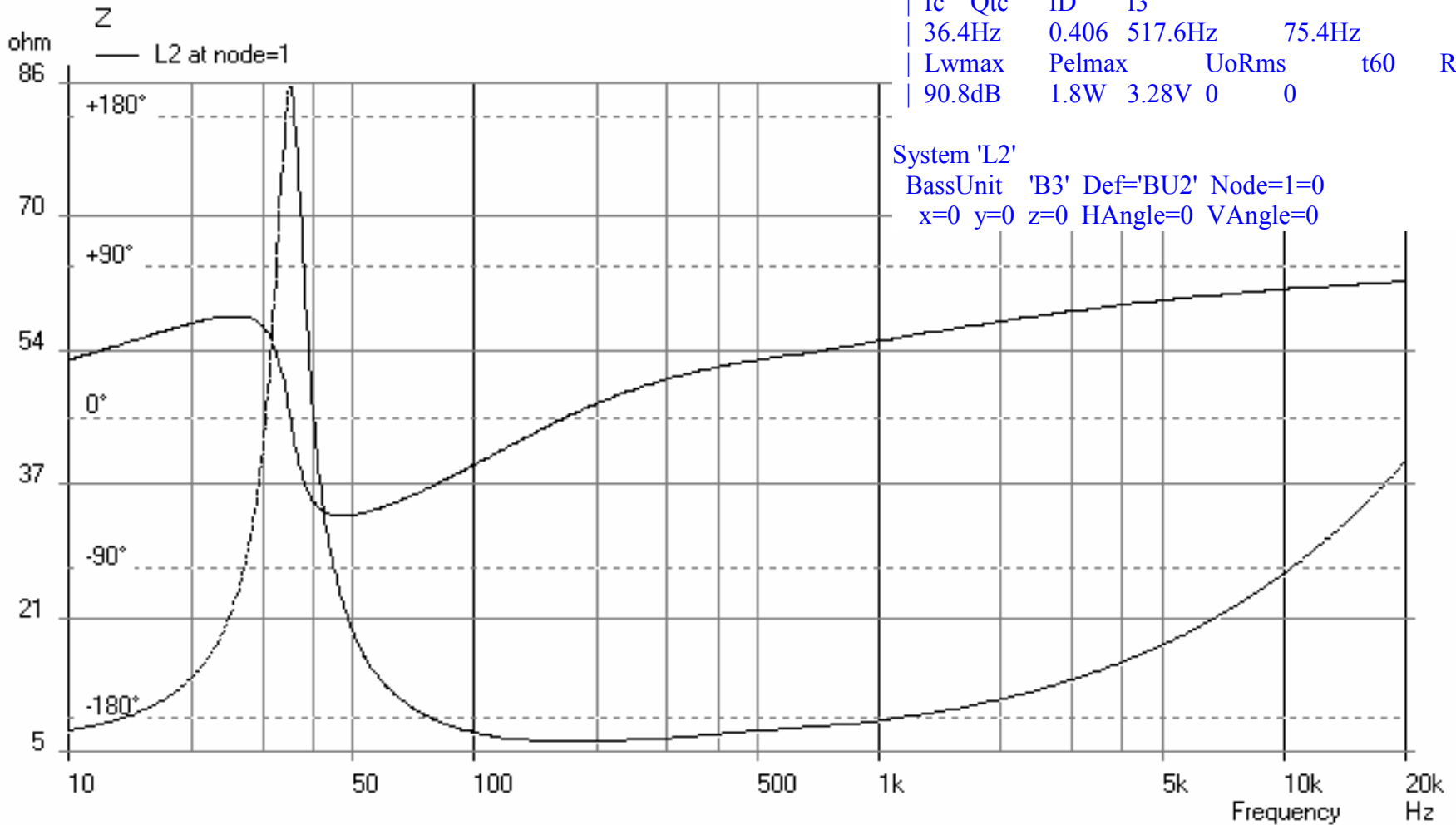
| 90.8dB 1.8W 3.28V 0 0

System 'L2'

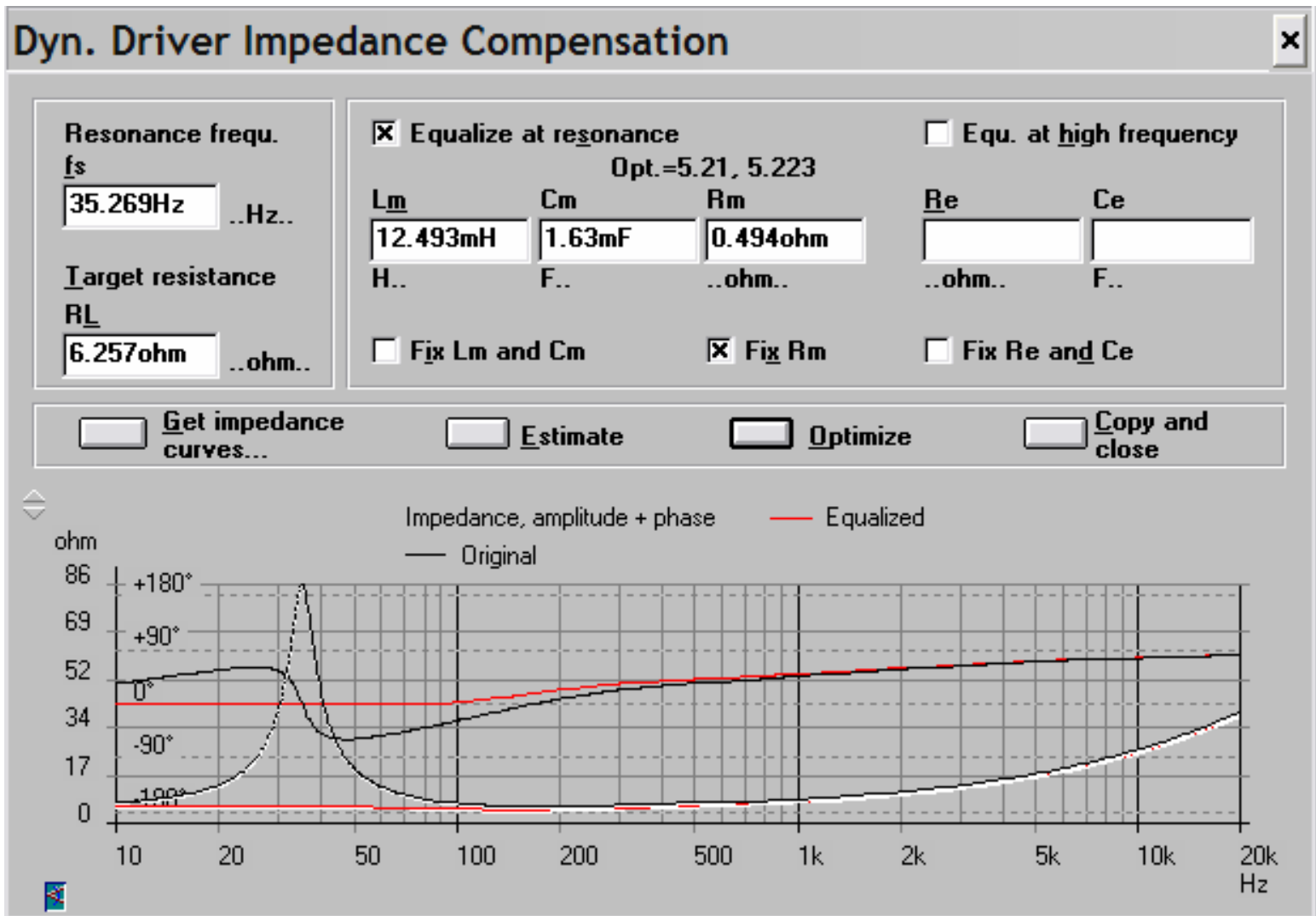
BassUnit 'B3' Def='BU2' Node=1=0

x=0 y=0 z=0 HAngle=0 VAngle=0

10. Impedance of L11B, Amplitude (Phase)



# Určenie sériového „antirezonančného“ RLC obvodu



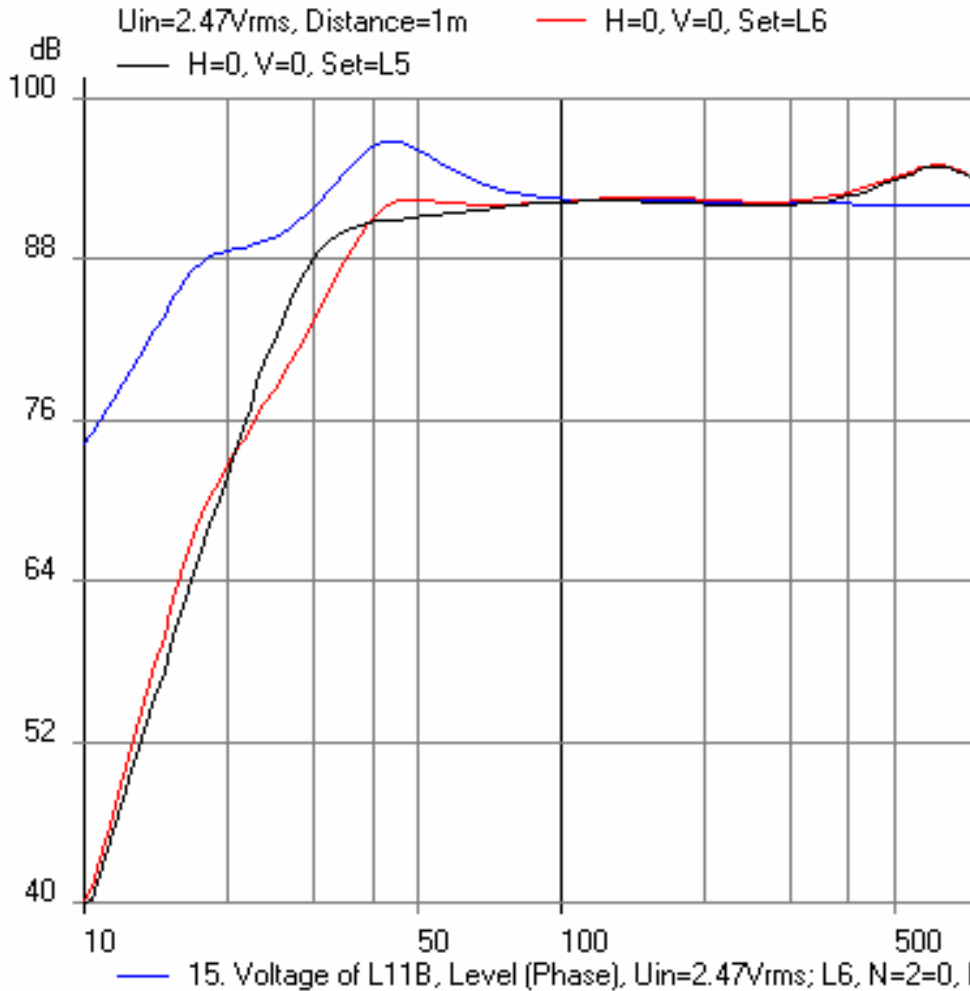
Def\_BassUnit 'BU4'  
 SD=350cm2 dD1=5.5cm tD1=6.5cm |Cone  
 fs=25Hz Vas=164L Qms=3.99  
 Qes=0.3 Re=6.1ohm Le=3.08mH ExpoLe=0.618  
 Xms=4mm

Vb=52.09L fb=26.0Hz Qb/fo=0.499  
 |Qe=1.696 fe=30.1Hz

Performance in vented enclosure:

fsb	Qtr	fD	f3		
25.0Hz		0.279	517.6Hz	32.3Hz	
Lwmax	Pelmax	UoRms	t60	Ripple	
97.4dB	8.0W	7V	45.73ms	0	

11. Sound Pressure of L11B, Lp (Phase)



System 'L6'

Capacitor Node=1=2 C=1.47mF  
 Coil Node=2=0 L=19.017mH

SynthesisInfo

Passive FirstNode=1 RL=6.1ohm QL=0  
 fo=30.1Hz vo=1  
 {b2=1;  
 a2=1; a1=0.5896; a0=1; }

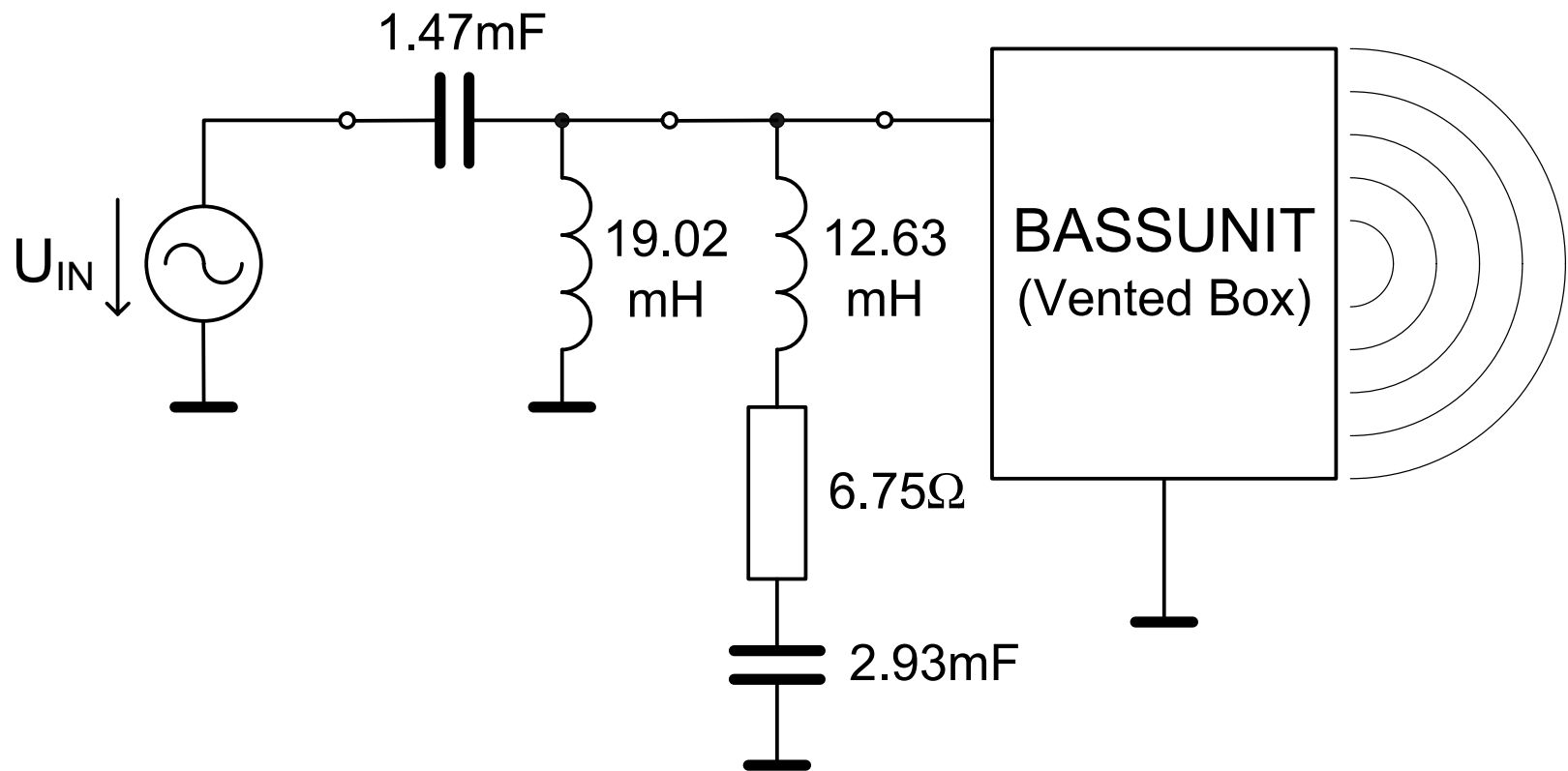
Impedance compensation

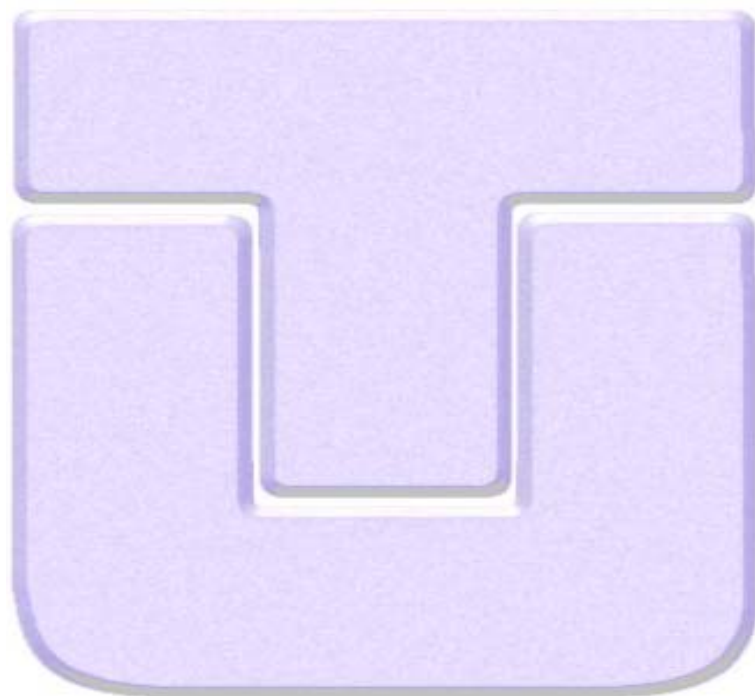
Capacitor Node=2=0 C=1.63mF Rs=6.751ohm Ls=12.494mH

BassUnit 'B4' Def='BU4' Node=2=0

x=0 y=0 z=0 HAngle=0 VAngle=0

# Schématické zapojenie tvarovacieho filtra s kompenzačným obvodom pre reproduktor v basreflexovej ozvučnici





$$\begin{aligned}
 H_{CB}(s) &= H_{HPF}(s) \cdot G_{CB}(s) = \frac{s_e^2}{s_e^2 + s_e/Q_e + 1} \frac{s_C^2}{s_C^2 + s_C/Q_{TC} + 1} = \\
 &= \frac{s_e^2 s_C^2}{s_e^2 s_C^2 + s_e s_C^2 / Q_e + s_C s_e^2 / Q_{TC} + s_e^2 + s_C^2 + s_e s_C / Q_{TC} Q_e + s_C / Q_{TC} + s_e / Q_e + 1} = \\
 &= \frac{s_0^4}{s_0^4 + s_0^3 \sqrt{\frac{\omega_e}{\omega_C}} \frac{1}{Q_e} + s_0^3 \sqrt{\frac{\omega_C}{\omega_e}} \frac{1}{Q_{TC}} + \frac{\omega_C}{\omega_e} s_0^2 + \frac{\omega_e}{\omega_C} s_0^2 + s_0^2 \frac{1}{Q_{TC} Q_e} + s_0 \sqrt{\frac{\omega_e}{\omega_C}} \frac{1}{Q_{TC}} + s_0 \sqrt{\frac{\omega_C}{\omega_e}} \frac{1}{Q_e} + 1}
 \end{aligned}$$

$$s_e = \frac{s}{\omega_e} \quad s_C = \frac{s}{\omega_C} \quad s_0 = \frac{s}{\omega_0} \quad \omega_0 = \sqrt{\omega_C \omega_e} = \omega_C \sqrt{h_e} = \frac{\omega_e}{\sqrt{h_e}}$$

$$h_e = \frac{\omega_e}{\omega_C}$$

$$\begin{aligned}
 &= \frac{s_0^4}{s_0^4 + \left( \frac{\sqrt{h_e}}{Q_e} + \frac{1}{\sqrt{h_e} Q_{TC}} \right) s_0^3 + \left( \frac{1}{h_e} + h_e + \frac{1}{Q_{TC} Q_e} \right) s_0^2 + \left( \frac{1}{\sqrt{h_e} Q_e} + \frac{\sqrt{h_e}}{Q_{TC}} \right) s_0 + 1}
 \end{aligned}$$

$$= \frac{s_0^4}{s_0^4 + a_3 s_0^3 + a_2 s_0^2 + a_1 s_0 + 1}$$

$$a_1 = \frac{1}{\sqrt{h_e} Q_e} + \frac{\sqrt{h_e}}{Q_{TC}}$$

$$a_2 = \frac{1}{h_e} + h_e + \frac{1}{Q_{TC} Q_e}$$

$$a_3 = \frac{\sqrt{h_e}}{Q_e} + \frac{1}{\sqrt{h_e} Q_{TC}}$$

**Prenosová funkcia  
reproduktora v zatvorenej  
ozvučnici s tvarovacím filtrom**



Aproximácia B4:

$$a_1 = \frac{1}{\sqrt{h_e} Q_e} + \frac{\sqrt{h_e}}{Q_{TC}} = 2.613$$

$$a_2 = \frac{1}{h_e} + h_e + \frac{1}{Q_{TC} Q_e} = 2 + \sqrt{2}$$

$$a_3 = \frac{\sqrt{h_e}}{Q_e} + \frac{1}{\sqrt{h_e} Q_{TC}} = 2.613$$

$$a_1 = a_3 \Rightarrow h_e = 1 \Rightarrow f_e = f_c$$

$$\left. \begin{array}{l} \frac{1}{Q_{TC} Q_e} = \sqrt{2} \\ \frac{1}{Q_e} + \frac{1}{Q_{TC}} = 2.613 \end{array} \right\} \Rightarrow \sqrt{2} Q_e^2 - 2.613 Q_e + 1 = 0$$
$$Q_{e1} = 1.307 \Rightarrow Q_{TC1} = 1/\sqrt{2} Q_{e1} = 0.541$$
$$Q_{e2} = 0.541 \Rightarrow Q_{TC2} = 1/\sqrt{2} Q_{e2} = 1.307$$

Def\_BassUnit 'BU1'

SD=350cm<sup>2</sup> dD1=5.5cm tD1=6.5cm |Cone

fs=25Hz Vas=164L Qms=3.99

Qes=0.3 Re=6.1ohm Le=3.08mH ExpoLe=0.618

Xms=4mm

Vb=59L

|Performance in sealed enclosure:

<b>fc</b>	<b>Qtc</b>	fD	f3	
<b>48.6Hz</b>	<b>0.542</b>	517.6Hz	67.3Hz	
Lwmax	Pelmax	UoRms	t60	Ripple
95.8dB	5.6W	5.86V	19.25ms	0

System 'L2'

Filter 'hpf'

**fo=48.6Hz** vo=1

{b2=1;

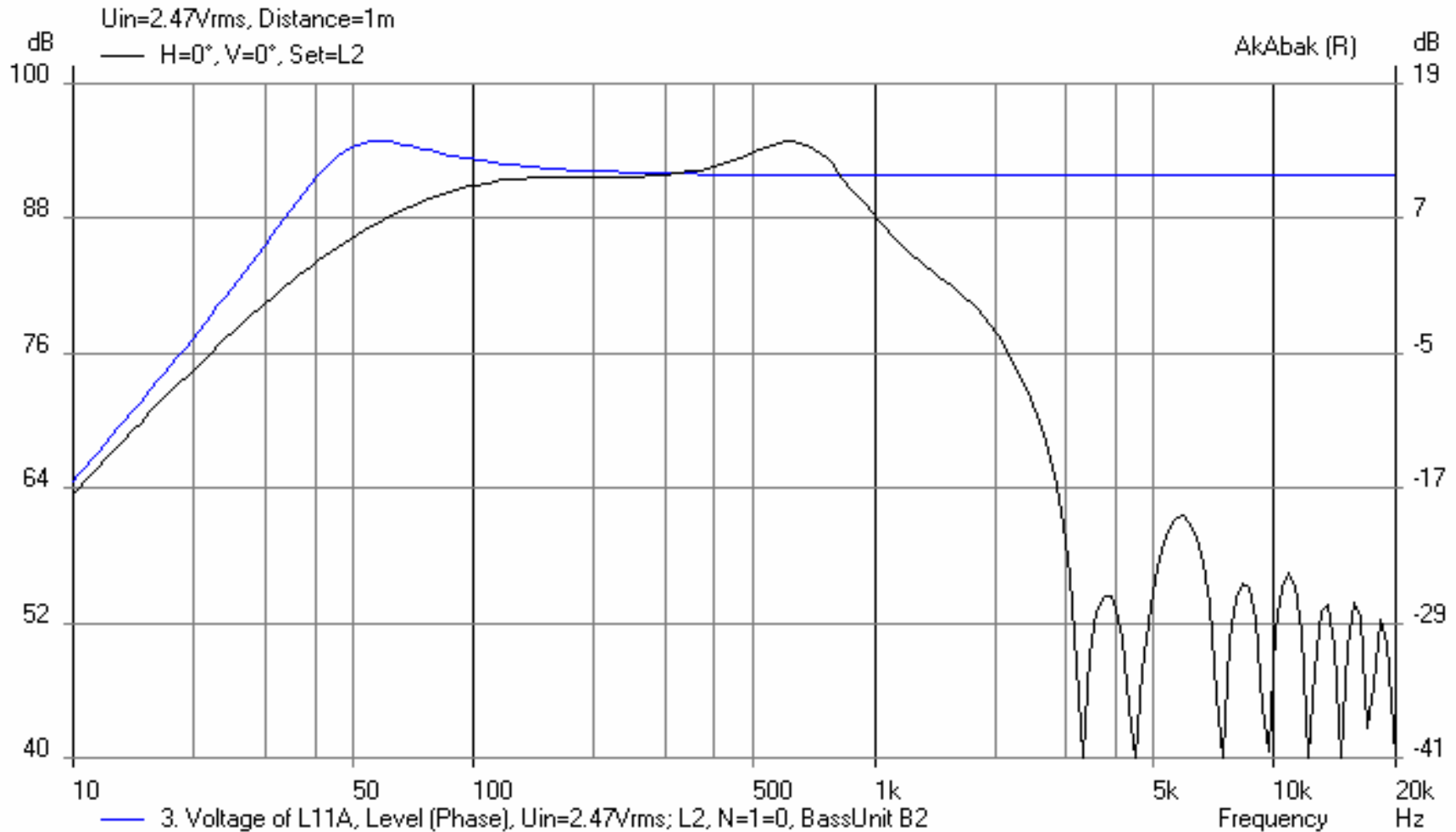
a2=1; **a1=0.765111**; a0=1; }

BassUnit 'B2' Def='BU1' Node=1=0

x=0 y=0 z=0 HAngle=0 VAngle=0

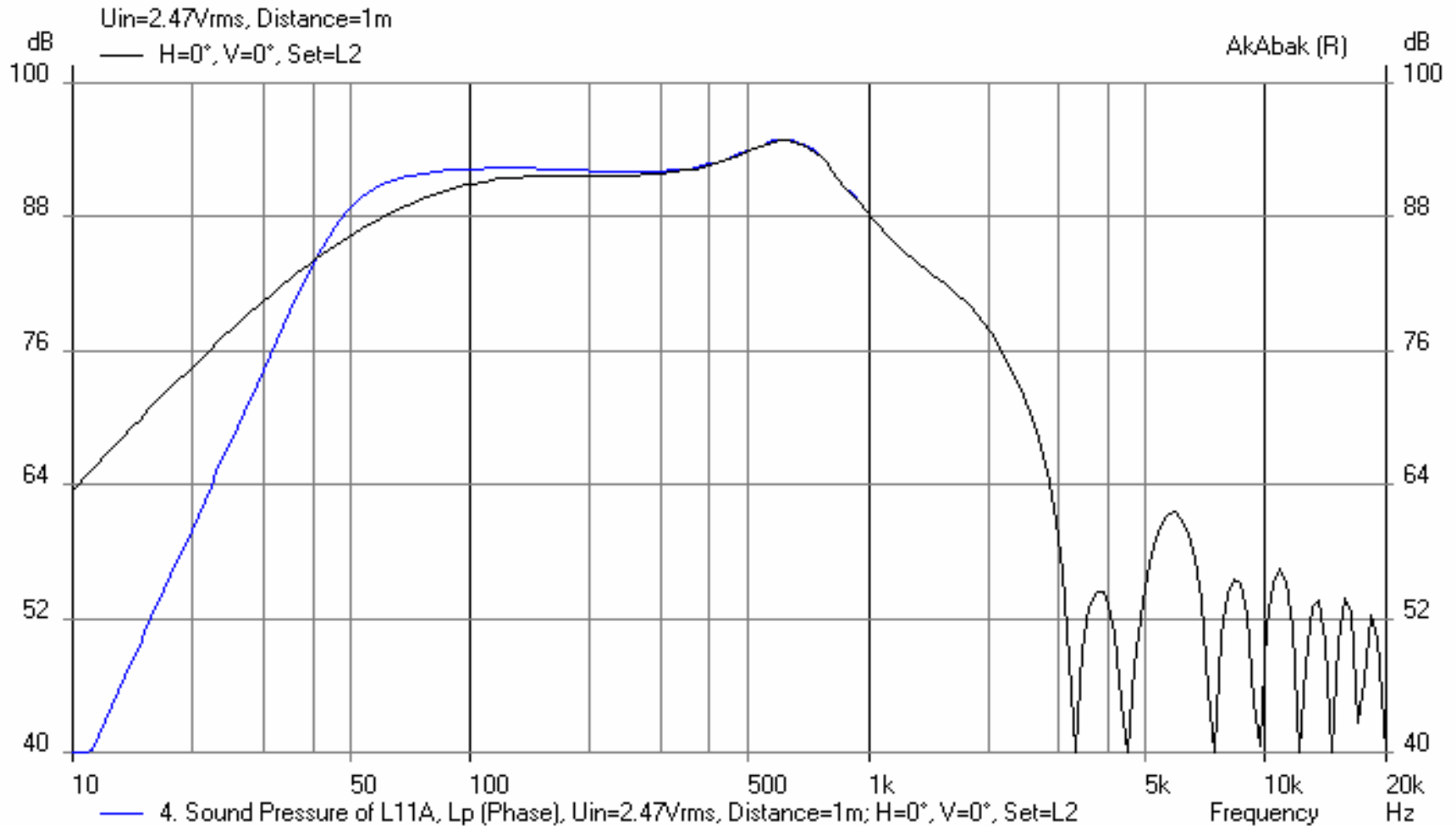
# AFCH reproduktora (CB) bez filtra a AFCH filtra

## 2. Sound Pressure of L11A, Lp (Phase)



# AFCH reproduktora (CB) bez filtra a s filtrom

## 2. Sound Pressure of L11A, Lp (Phase)



Aproximácia LR4:

$$a_1 = \frac{1}{\sqrt{h_e} Q_e} + \frac{\sqrt{h_e}}{Q_{TC}} = 2.828$$

$$a_2 = \frac{1}{h_e} + h_e + \frac{1}{Q_{TC} Q_e} = 4$$

$$a_3 = \frac{\sqrt{h_e}}{Q_e} + \frac{1}{\sqrt{h_e} Q_{TC}} = 2.828$$

$$a_1 = a_3 \Rightarrow h_e = 1 \Rightarrow f_e = f_C$$

$$\left. \begin{array}{l} \frac{1}{Q_{TC} Q_e} = 2 \\ \frac{1}{Q_e} + \frac{1}{Q_{TC}} = 2.828 \end{array} \right\} \Rightarrow \begin{array}{l} 2Q_e^2 - 2.828Q_e + 1 = 0 \\ Q_e = 0.707 \Rightarrow Q_{TC} = \frac{1}{2Q_{e1}} = 0.707 \end{array}$$

