TECHNICKÁ UNIVERZITA V KOŠICIACH

Elektroakustika

L10: Reproduktorové sústavy

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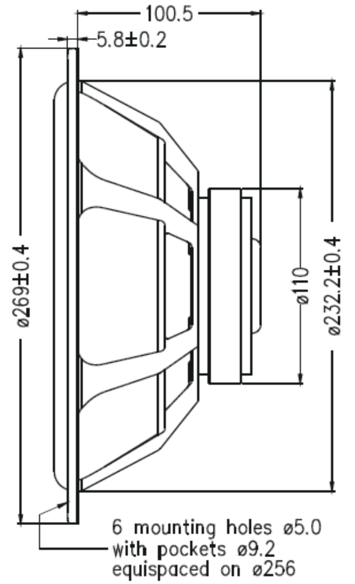
http://voice.kemt.fei.tuke.sk

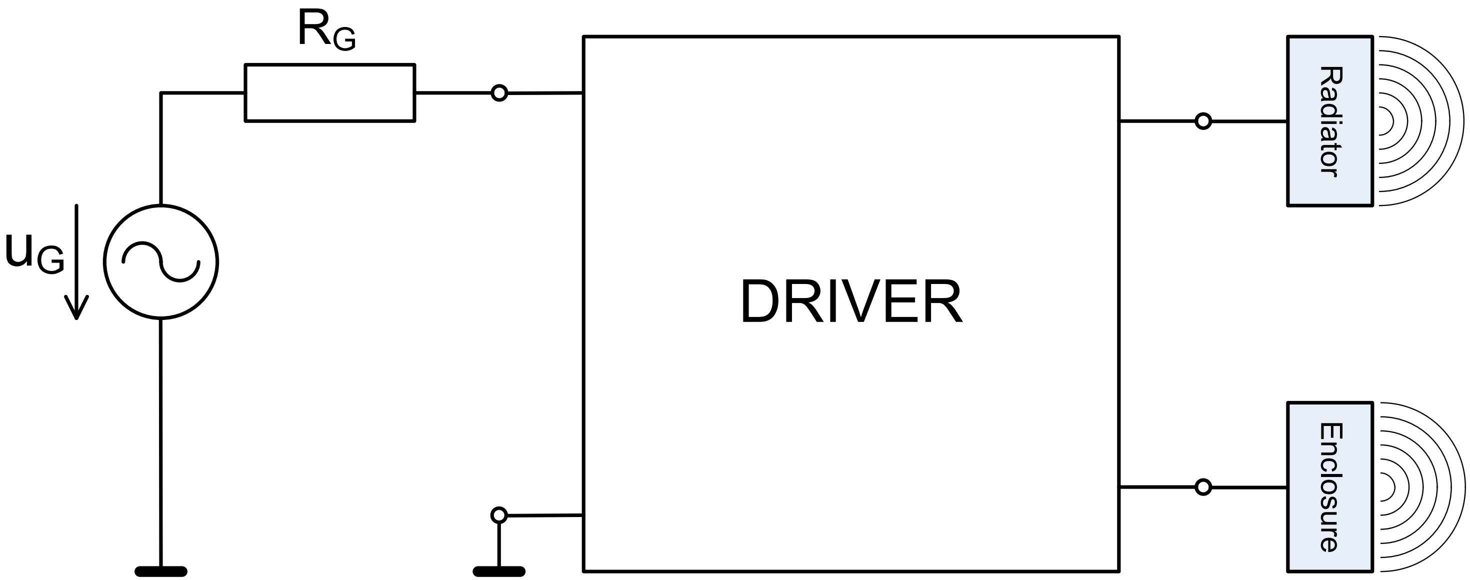
Nízkotónový reproduktor



Nominal Impedance	8 Ohms	Voice Coil Resistance	6.1 Ohms
Recommended Frequency Range	30 - 1500 Hz	Voice Coil Inductance	3.08 mH
Short Term Power Handling *	300 W	Force Factor	11.6 N/A
Long Term Power Handling *	80 W	Free Air Resonance	25 Hz
Characteristic Sensitivity (2.83V, 1m)	91 dB	Moving Mass	38.5 g
Voice Coil Diameter	39 mm	Air Load Mass In IEC Baffle	3.8 g
Voice Coil Height	14 mm	Suspension Compliance	1.1 mm/N
Air Gap Height	6 mm	Suspension Mechanical Resistance	1.66 Ns/m
Linear Coil Travel (p-p)	8 mm	Effective Piston Area	350 cm^2
Maximum Coil Travel (p-p)	20 mm	VAS	164 Litres
Magnetic Gap Flux Density	0.9 T	QMS	3.99
Magnet Weight	0.64 kg	QES	0.30
Total Weight	2.17 kg	QTS	0.28

Nízkotónový reproduktor v basreflexovej ozvučnici

(Driver, Radiator, Enclosure)

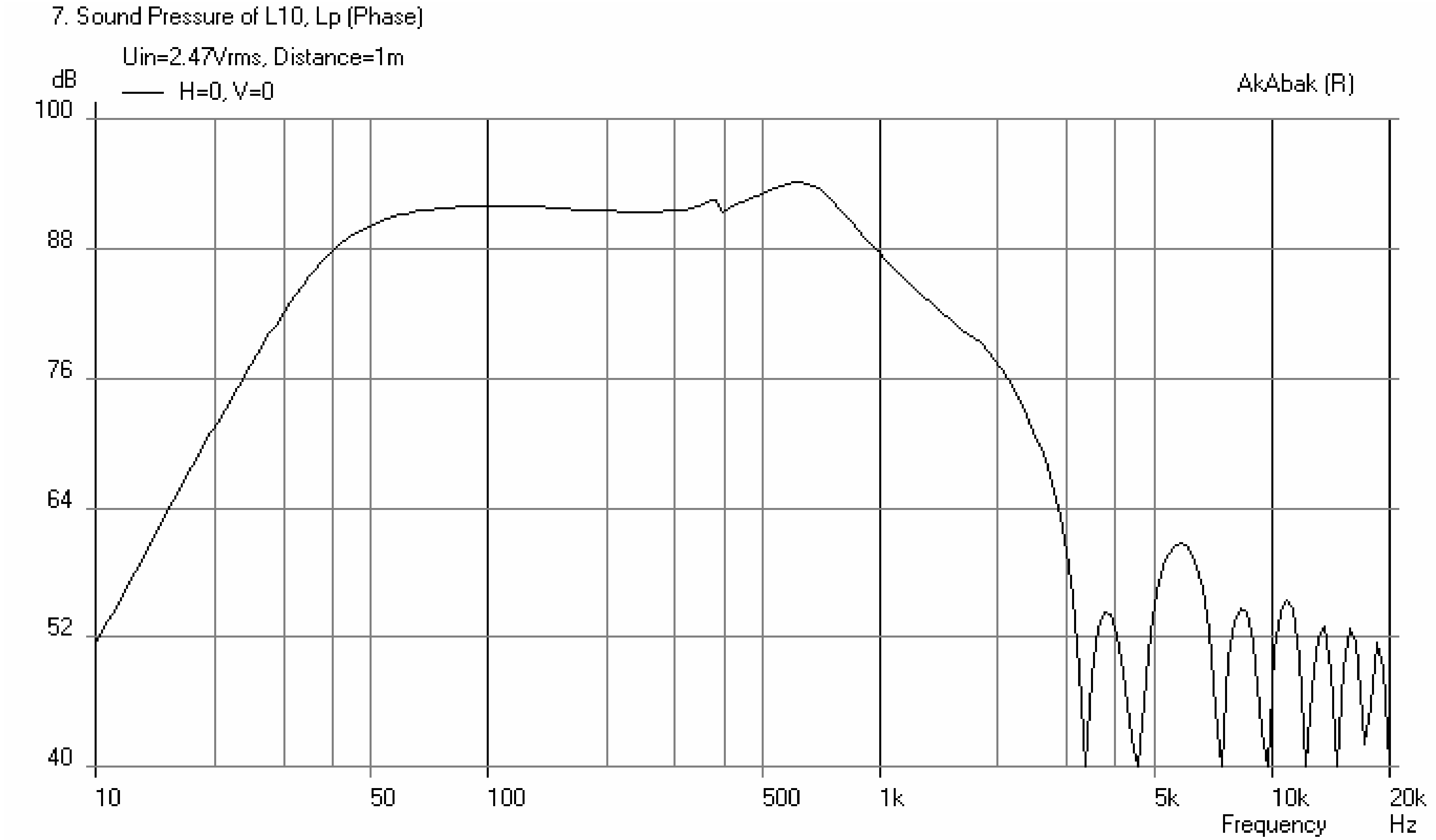


- α=3.65, h=1.35, q=1.7
- Dp,min=10cm

Skript nízkotónovej časti

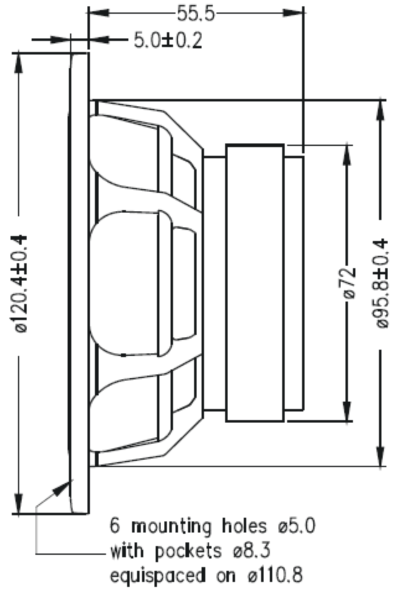
```
| Seas Prestige CA26RE4X H1316
| Revc=6.1Ohms; Levc=3.08mH; Bl=11.6N/A; Mmd=38.5g;
| Mmrd=3.8g; Rms=1.66Ns/m; Cms=1.1mm/N; Sd=350cm2
| Fs=25Hz; Qts=0.28; Qms=3.99; Qes=0.30; Vas=164lit;
| ymax=4mm; sens=91dB; Pe(lt)=80W

Def_Driver  'Woofer'
  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

System 'L'
  Driver 'D1'  Def='Woofer'  Node=1=0=2=3
  Radiator  'Rad1'  Def='D1'   Node=2
    x=0  y=0  z=0  HAngle=0  VAngle=0
  Enclosure   'E1'  Node=3
    Vb=45L  Sb=350cm2
    fb=34Hz  dD=10cm  QD/fo=0.34  Visc=0
    x=0  y=0  z=0  HAngle=0  VAngle=0
```

Hladina akustického tlaku



Stredotónový reproduktor

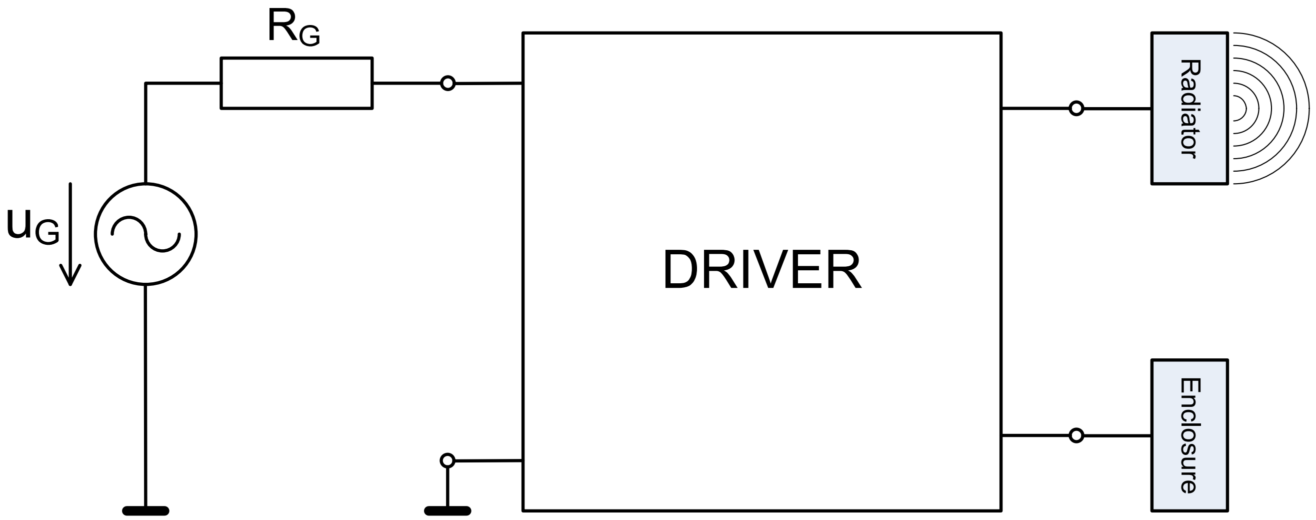
- QTC=0.9; a=1.58;



Nominal Impedance	8 Ohms	Voice Coil Resistance	6.3 Ohms
Recommended Frequency Range	400 - 5000 Hz	Voice Coil Inductance	0.31 mH
Short Term Power Handling *	400 W	Force Factor	4.2 N/A
Long Term Power Handling *	110 W	Free Air Resonance	68 Hz
Characteristic Sensitivity (2.83V, 1m)	86.0 dB	Moving Mass	4.58 g
Voice Coil Diameter	26 mm	Air Load Mass In IEC Baffle	0.24 g
Voice Coil Height	5.8 mm	Suspension Compliance	1.2 mm/N
Air Gap Height	4.0 mm	Suspension Mechanical Resistance	0.85 Ns/m
Linear Coil Travel (p-p)	1.8 mm	Effective Piston Area	55 cm^2
Maximum Coil Travel (p-p)	-	VAS	5 Litres
Magnetic Gap Flux Density	1.1 T	QMS	2.42
Magnet Weight	0.25 kg	QES	0.74
Total Weight	0.66 kg	QTS	0.56

Stredotónový reproduktor v zatvorenej ozvučnici

(Driver, Radiator, Enclosure)

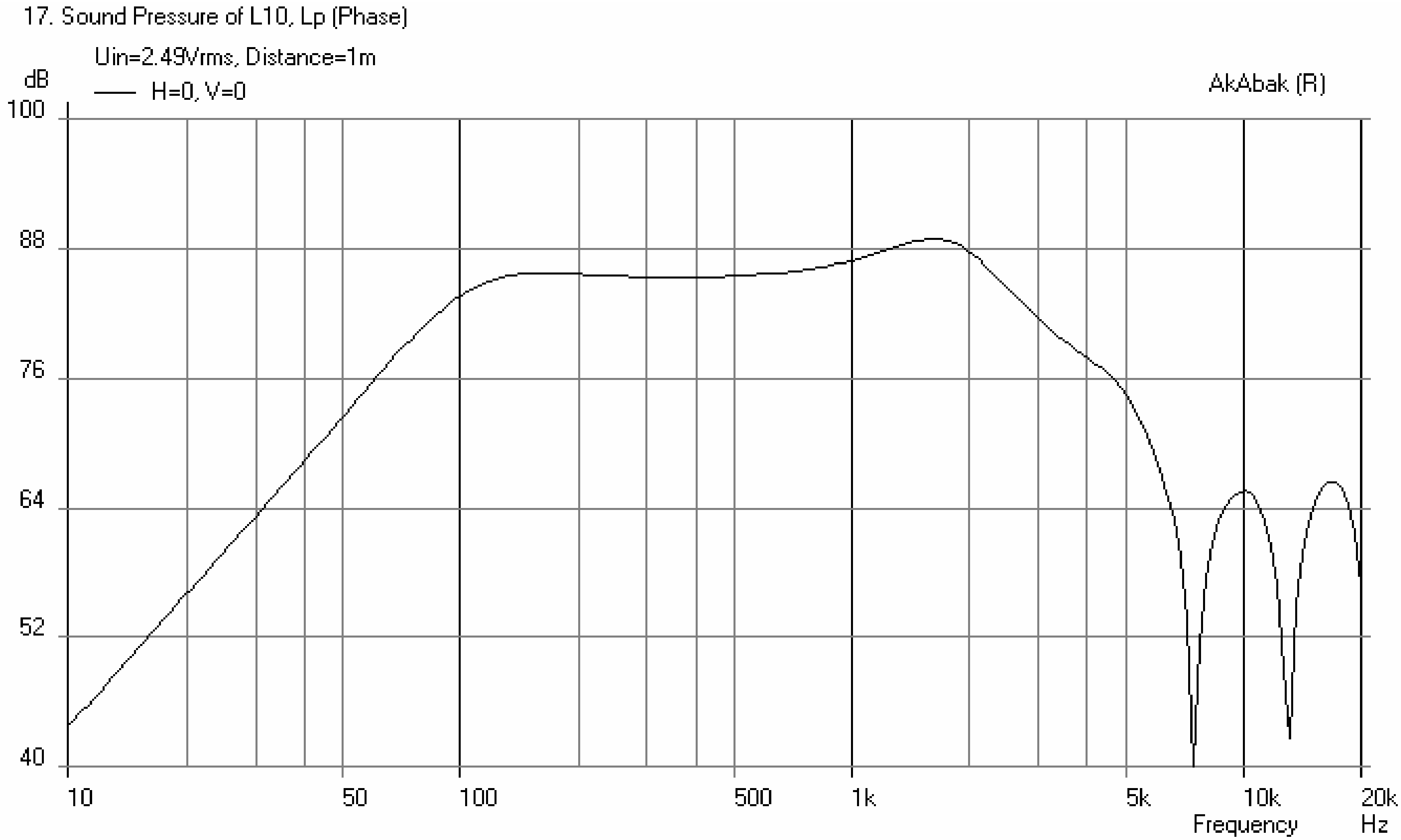


- QTC=0.9; a=1.58;

Skript stredotónovej časti

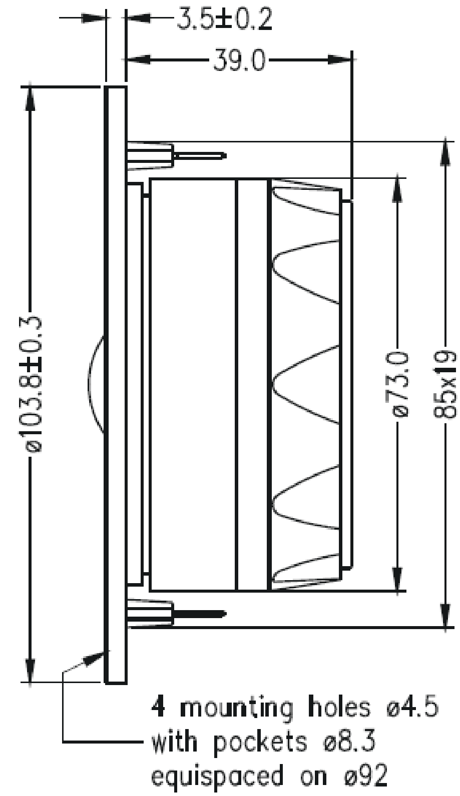
```
| Seas Prestige MCA12RC H1304
| Revc=6.3Ohms; Levc=0.31mH; Bl=4.2N/A; Mmd=4.58g;
|Mmrd=0.24g; Rms=0.85Ns/m; Cms=1.2mm/N;
|Sd=55cm2; Fs=68Hz; Qts=0.56; Qms=2.42; Qes=0.74; Vas=5lit.;
|ymax=0.9mm; sens=86dB; Pe(lt)=110W

Def_Driver  'Midrange'
  SD=55cm2  dD1=3.6cm  tD1=2.75cm   |Cone
  fs=68Hz  Vas=5L  Qms=2.42
  Qes=0.74  Re=6.2ohm  Le=0.31mH  ExpoLe=0.618

System 'M'
  Driver 'D2'  Def='Midrange'  Node=1=0=4=5
  Radiator  'Rad1'  Def='D2'    Node=4
    x=0  y=0  z=0  HAngle=0  VAngle=0
  Enclosure    'E2'  Node=5
    Vb=1.75L  Sb=55cm2
```

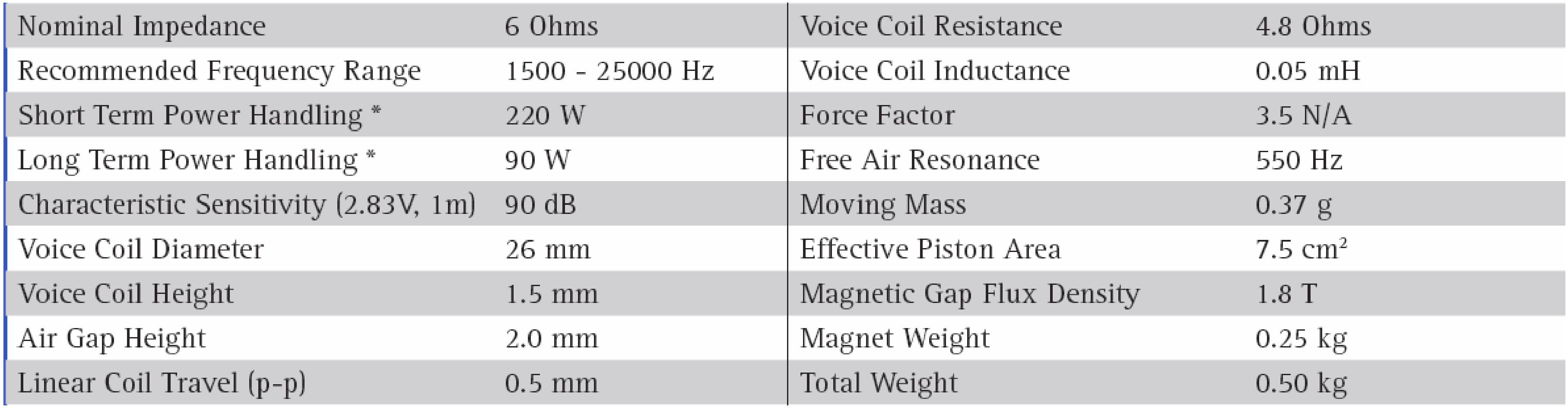
Hladina akustického tlaku stredotónovej časti



Vysokotónový reproduktor

- …



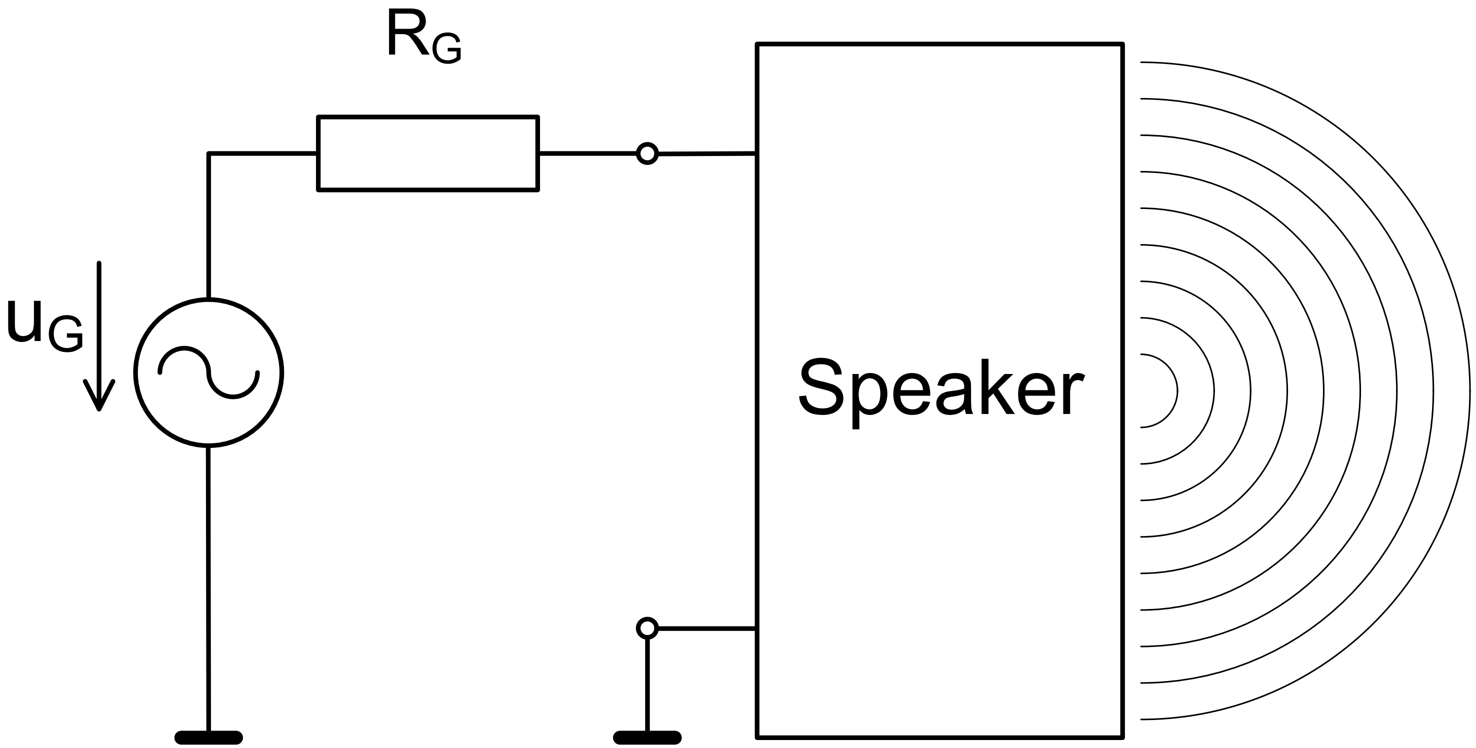


Nominal Impedance	6 Ohms	Voice Coil Resistance	4.8 Ohms
Recommended Frequency Range	1500 - 25000 Hz	Voice Coil Inductance	0.05 mH
Short Term Power Handling *	220 W	Force Factor	3.5 N/A
Long Term Power Handling *	90 W	Free Air Resonance	550 Hz
Characteristic Sensitivity (2.83V, 1m)	90 dB	Moving Mass	0.37 g
Voice Coil Diameter	26 mm	Effective Piston Area	7.5 cm²
Voice Coil Height	1.5 mm	Magnetic Gap Flux Density	1.8 T
Air Gap Height	2.0 mm	Magnet Weight	0.25 kg
Linear Coil Travel (p-p)	0.5 mm	Total Weight	0.50 kg

Vysokotónový reproduktor

(Speaker)

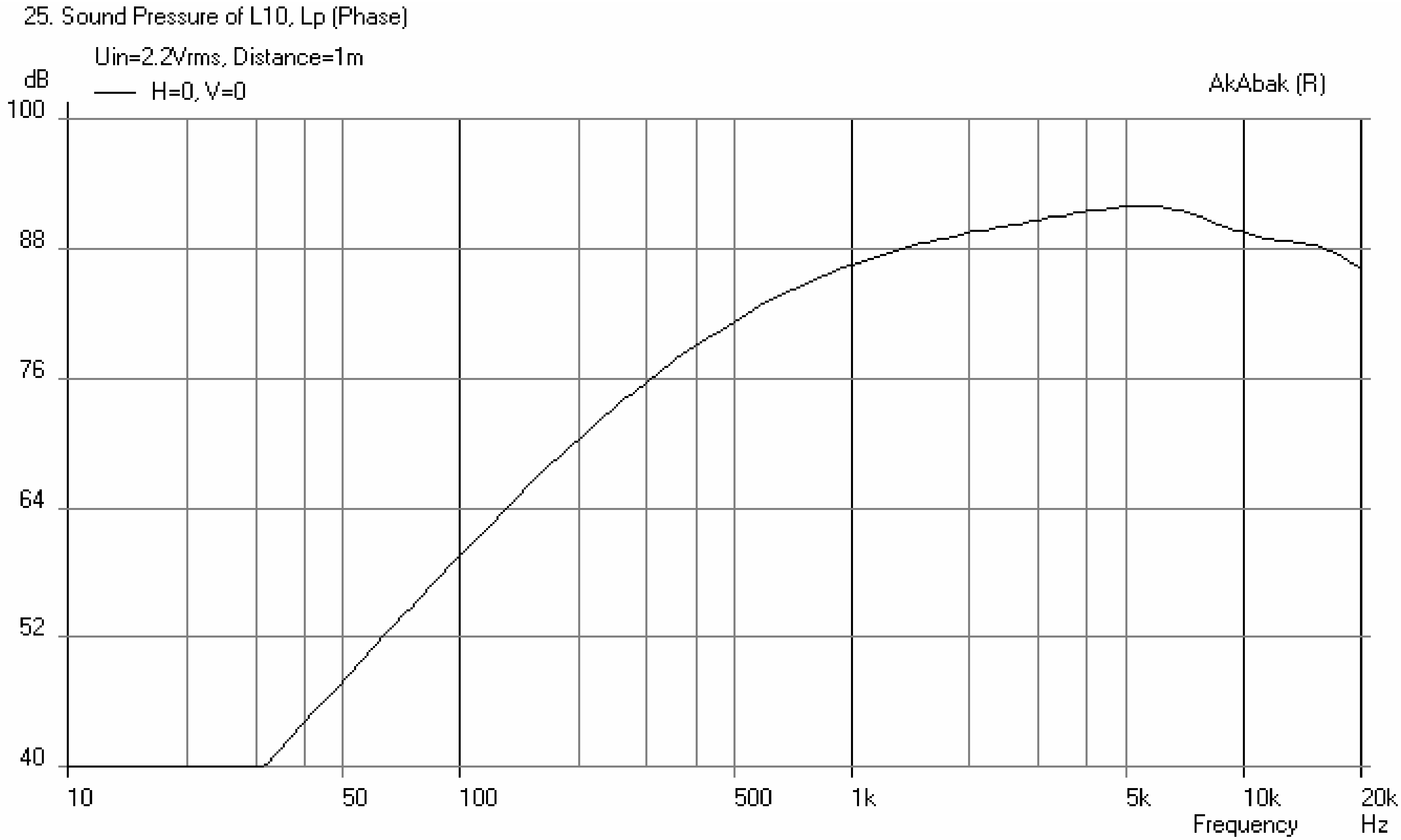
- …



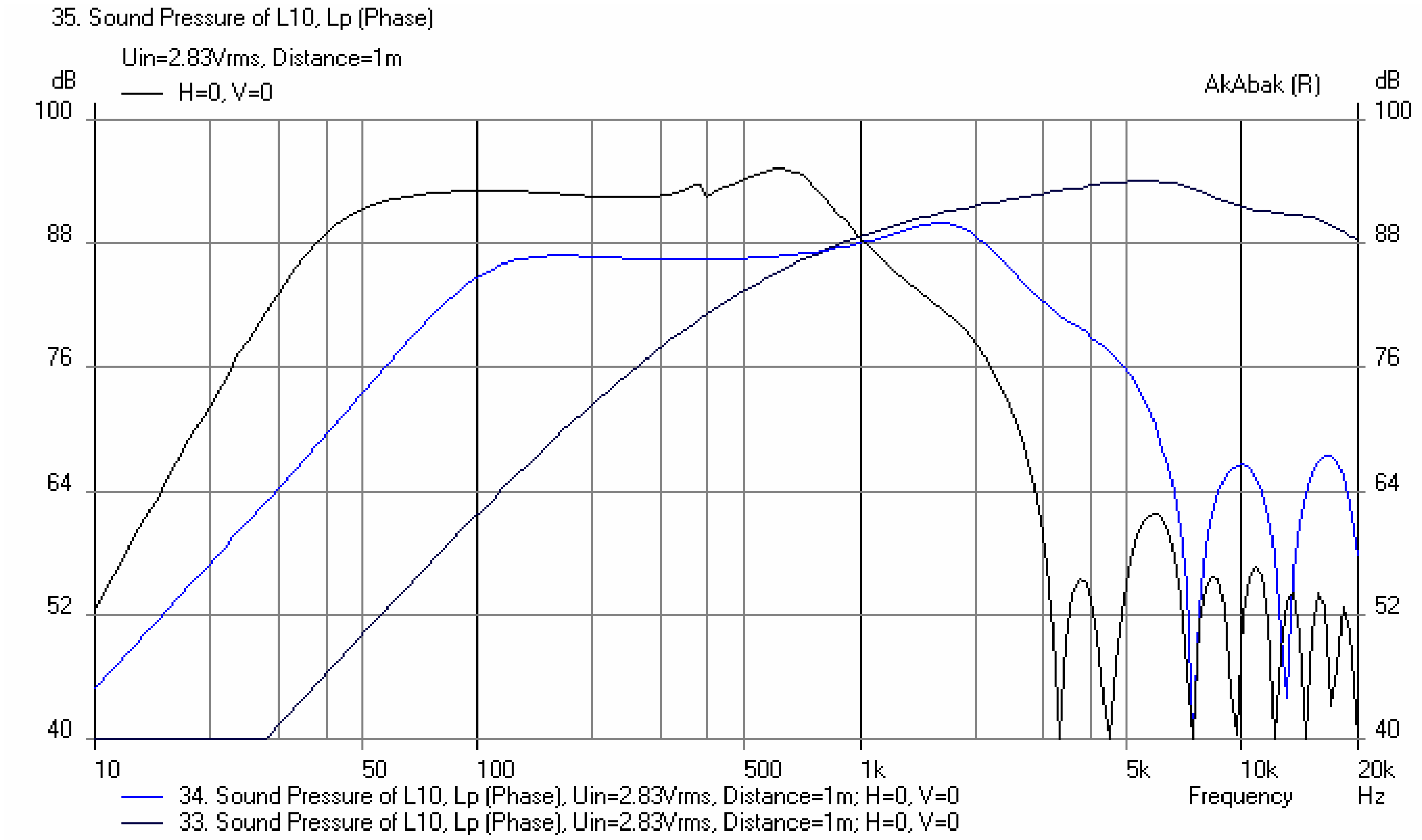
Skript vysokotónovej časti

```
| Seas Prestige 27TDFC H1189
| Revc=4.8Ohms; Levc=0.05mH; Bl=3.5N/A; Mms=0.37g; Sd=7.5cm2
| Fs=550Hz; ymax=0.25mm; sens=90dB; Pe(lt)=90W

Def_Speaker  'Tweeter'
  Meas_Dipole
  SD=7.5cm2  tD1=5.5mm t1=3.5mm  |Convex Dome
  fs=550Hz  Vas=17.8cm3  Qms=2.425
  Bl=3.5Tm  Re=4.8ohm  Le=50uH  ExpoLe=0.618

System 'T'
  Speaker    'Sp1'  Def='Tweeter'  Node=1=0
    x=0  y=0  z=0  HAngle=0  VAngle=0
```

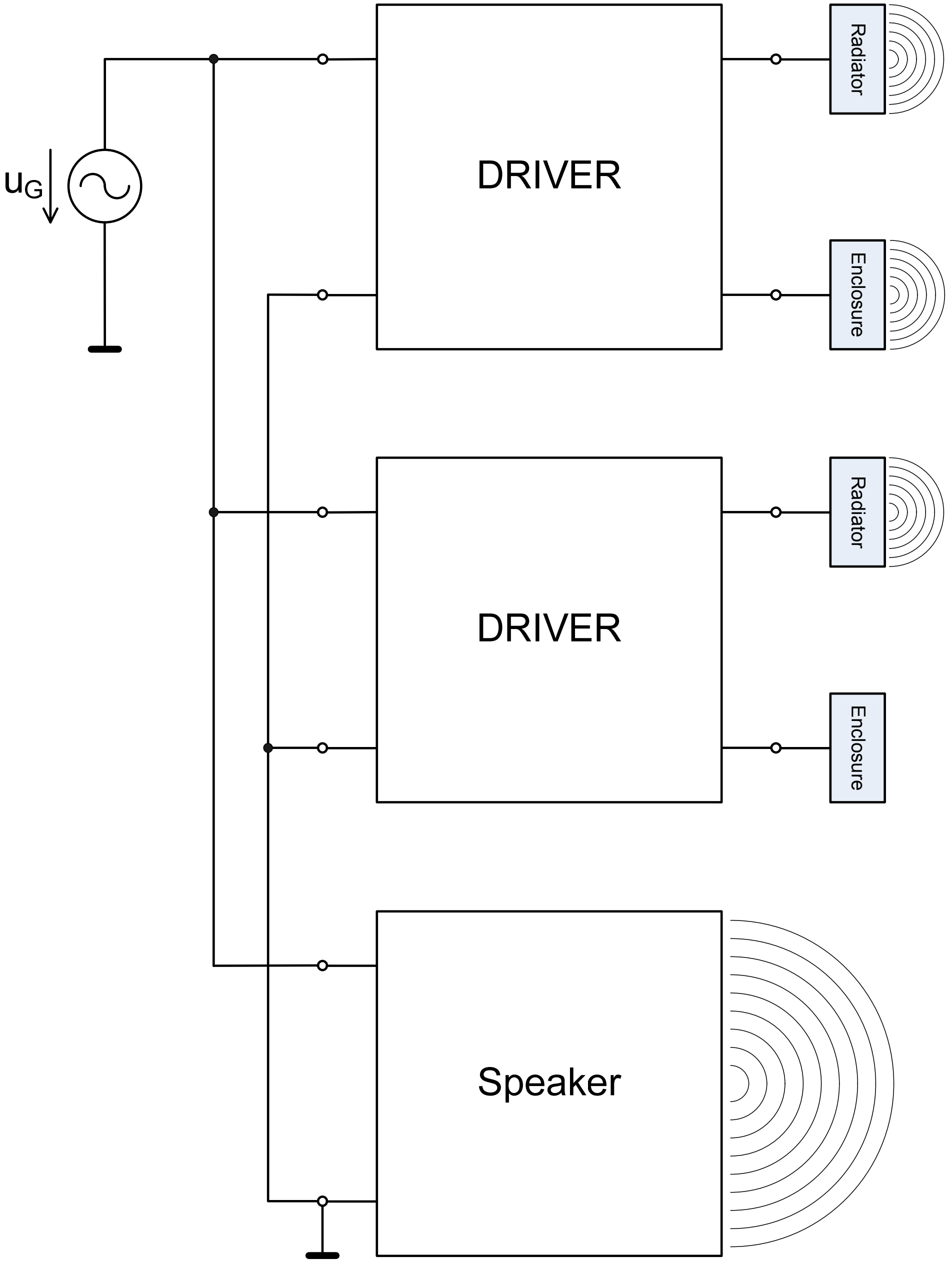
Hladina akustického tlaku



Hladiny akustických tlakov v troch subpásmach - porovnanie



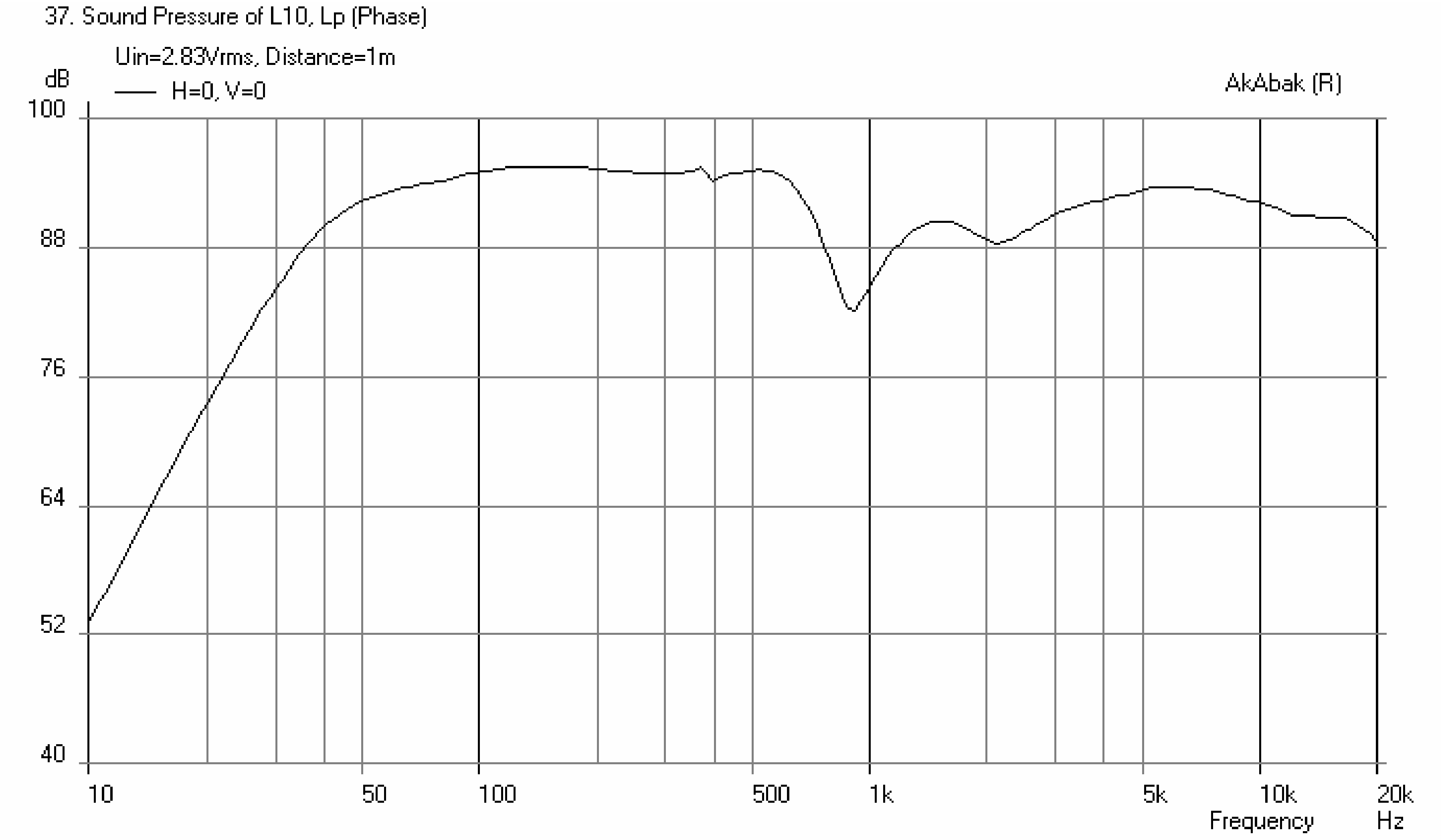
Všetky tri reproduktory dohromady



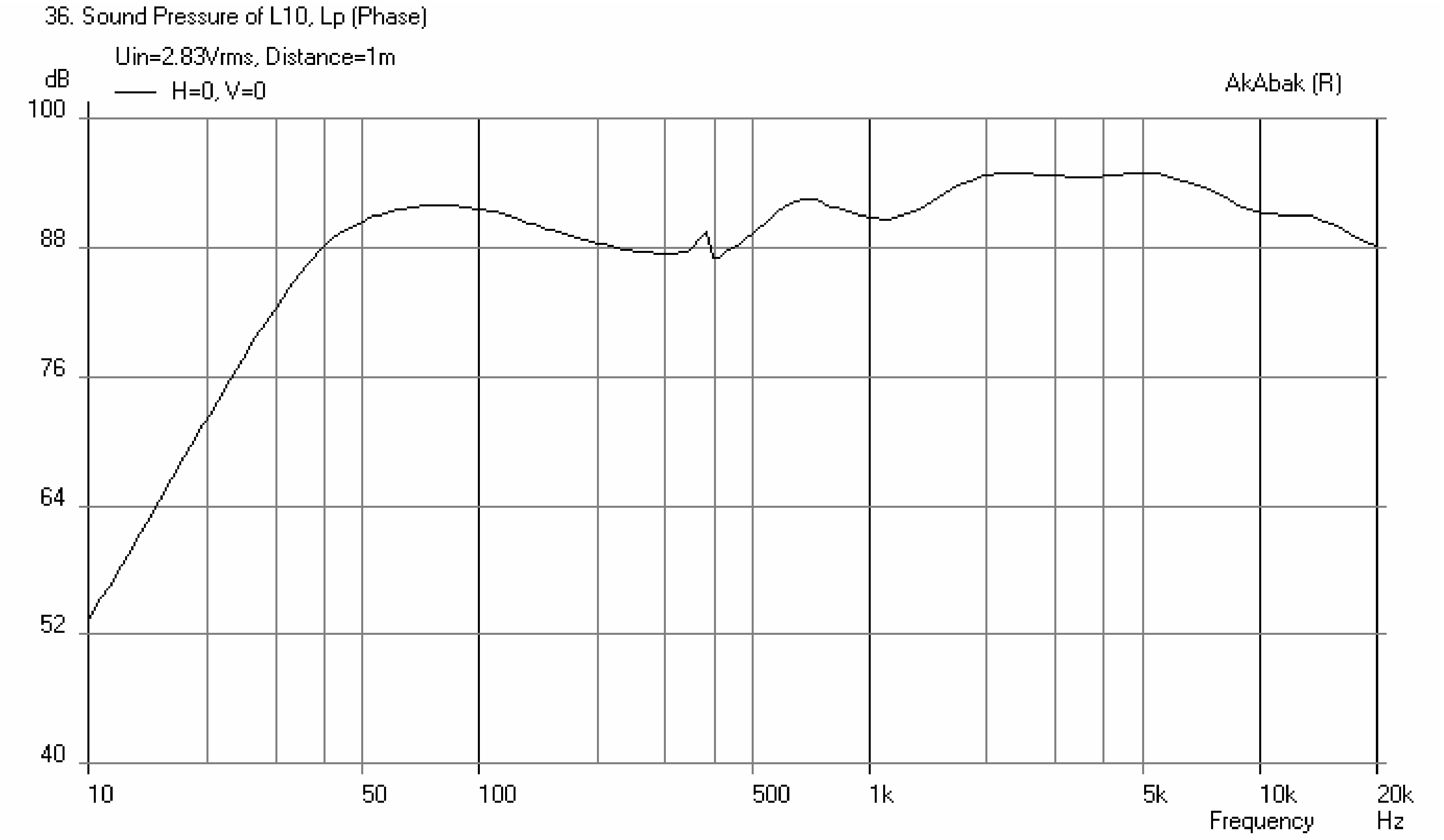
Skript

```
Def_Driver  'Woofer'
 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

Def_Driver  'Midrange'
 SD=55cm2  dD1=3.6cm  tD1=2.15cm   |Cone
 fs=68Hz  Vas=5L  Qms=2.42  Qes=0.74  Re=6.2ohm  Le=0.31mH  ExpoLe=0.618

Def_Speaker  'Tweeter'
 Meas_Dipole
 SD=7.5cm2  tD1=5.5mm t1=3.5mm  |Convex Dome
 fs=550Hz  Vas=17.8cm3  Qms=2.425  Bl=3.5Tm  Re=4.8ohm  Le=50uH  ExpoLe=0.618

System 'L'
 Driver 'D1'  Def='Woofer'  Node=1=0=2=3
 Radiator  'Rad1'  Def='D1'   Node=2
  x=0  y=0  z=0  HAngle=0  VAngle=0
 Enclosure   'E1'  Node=3
  Vb=45L  Sb=350cm2  fb=34Hz  dD=10cm  QD/fo=0.34  Visc=0
  x=0  y=0  z=0  HAngle=0  VAngle=0

System 'M'
 Driver 'D2'  Def='Midrange'  Node=1=0=4=5
 Radiator  'Rad1'  Def='D2'   Node=4
  x=0  y=0  z=0  HAngle=0  VAngle=0
 Enclosure   'E2'  Node=5
  Vb=3.2L  Sb=55cm2

System 'T'
 Speaker   'Sp1'  Def='Tweeter'  Node=1=0
  x=0  y=0  z=0  HAngle=0  VAngle=0
```

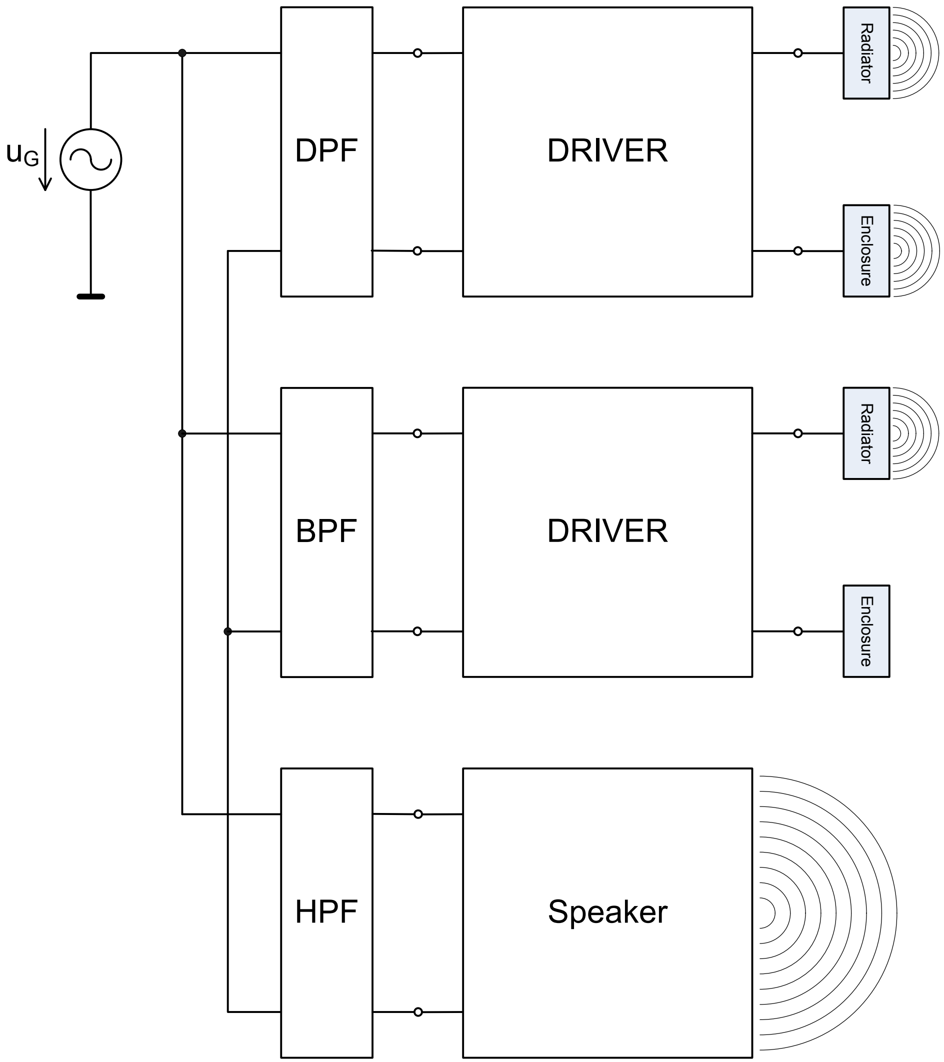
Celková hladina akustického tlaku pri rovnakej polarite reproduktorov



Celková hladina akustického tlaku: opačná polarita stredotónového reproduktora



Použitie elektrických filtrov vo funkcii „výhybiek“

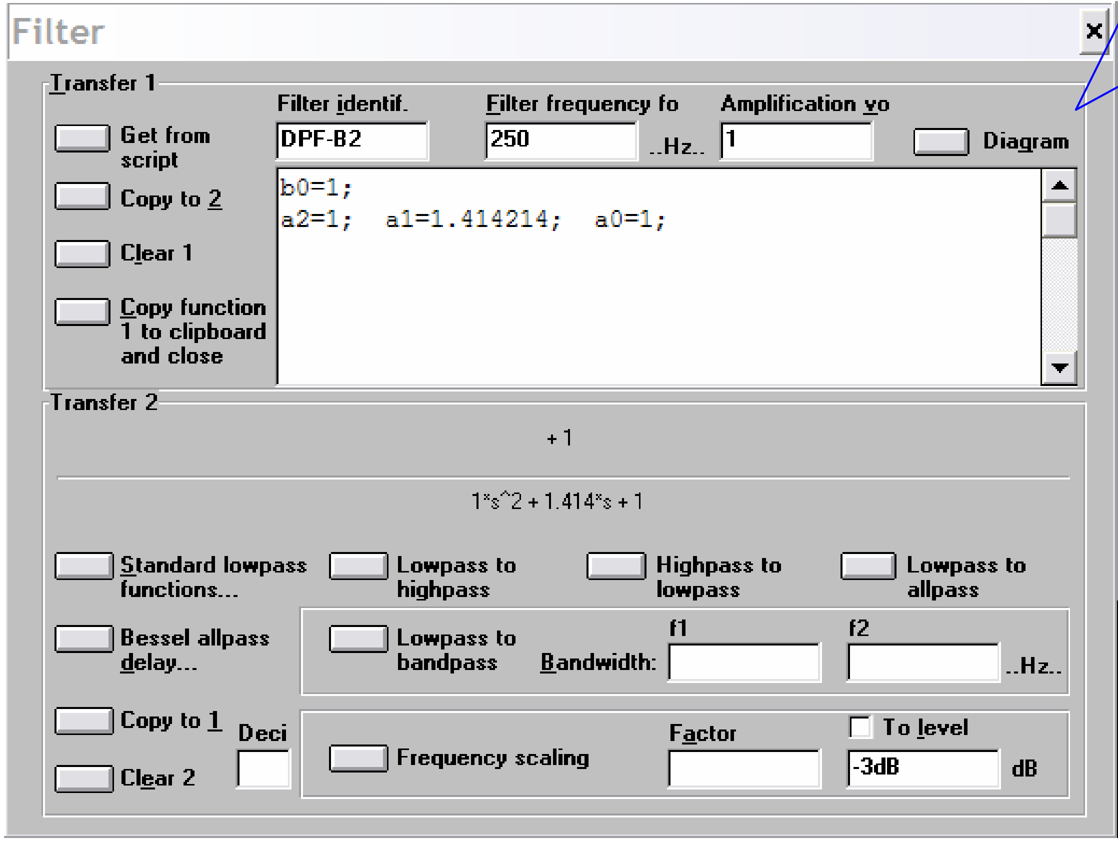


Filter-Dialog: Dolnopriepustný filter

(Butterworth, 2. rád)

$$H(s) = \frac{1}{s_0^{\,2} + 1.414214 s_0 + 1} \qquad s_0 = \frac{s}{\omega_0}$$

1. Standard Lowpass Functions
2. Výber „Order“ a „Class“ filtra
3. Copy to 1
4. Vloženie „Filter identif.“, „Filter frequency f0“ a „Amplification“
5. Copy function 1 to clipboard and close



Filter identif.: DPF-B2

Filter frequency fo: 250 ..Hz..

Amplification vo: 1

```
b0=1;
a2=1;   a1=1.414214;   a0=1;
```

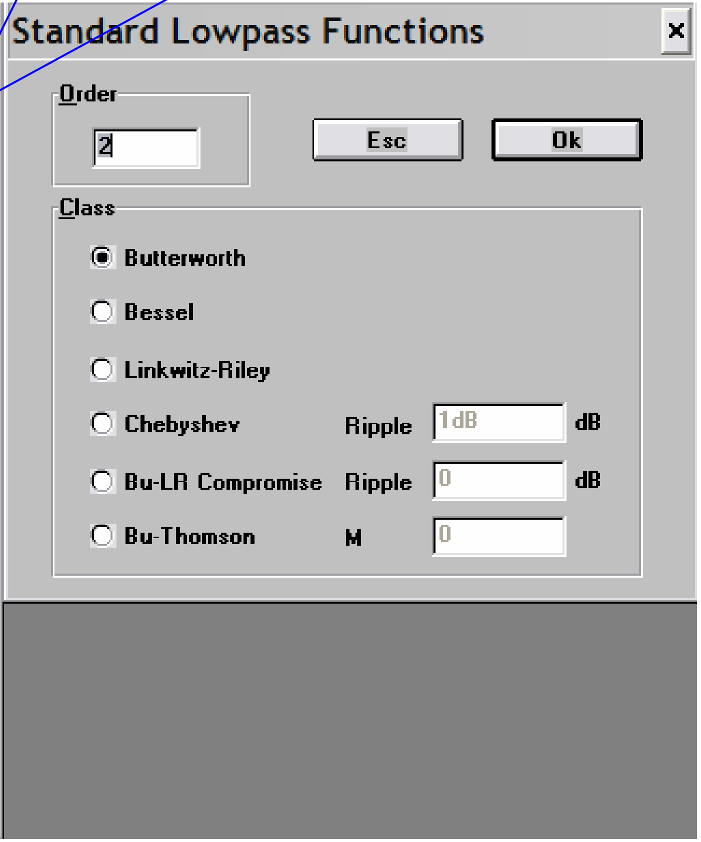
+1

1*s^2+1.414*s+1

Bandwidth: f1 ______ f2 ______ ..Hz..

Factor ______

☐ To level -3dB dB



Order: 2

Class

● Butterworth

○ Bessel

○ Linkwitz-Riley

○ Chebyshev Ripple 1dB dB

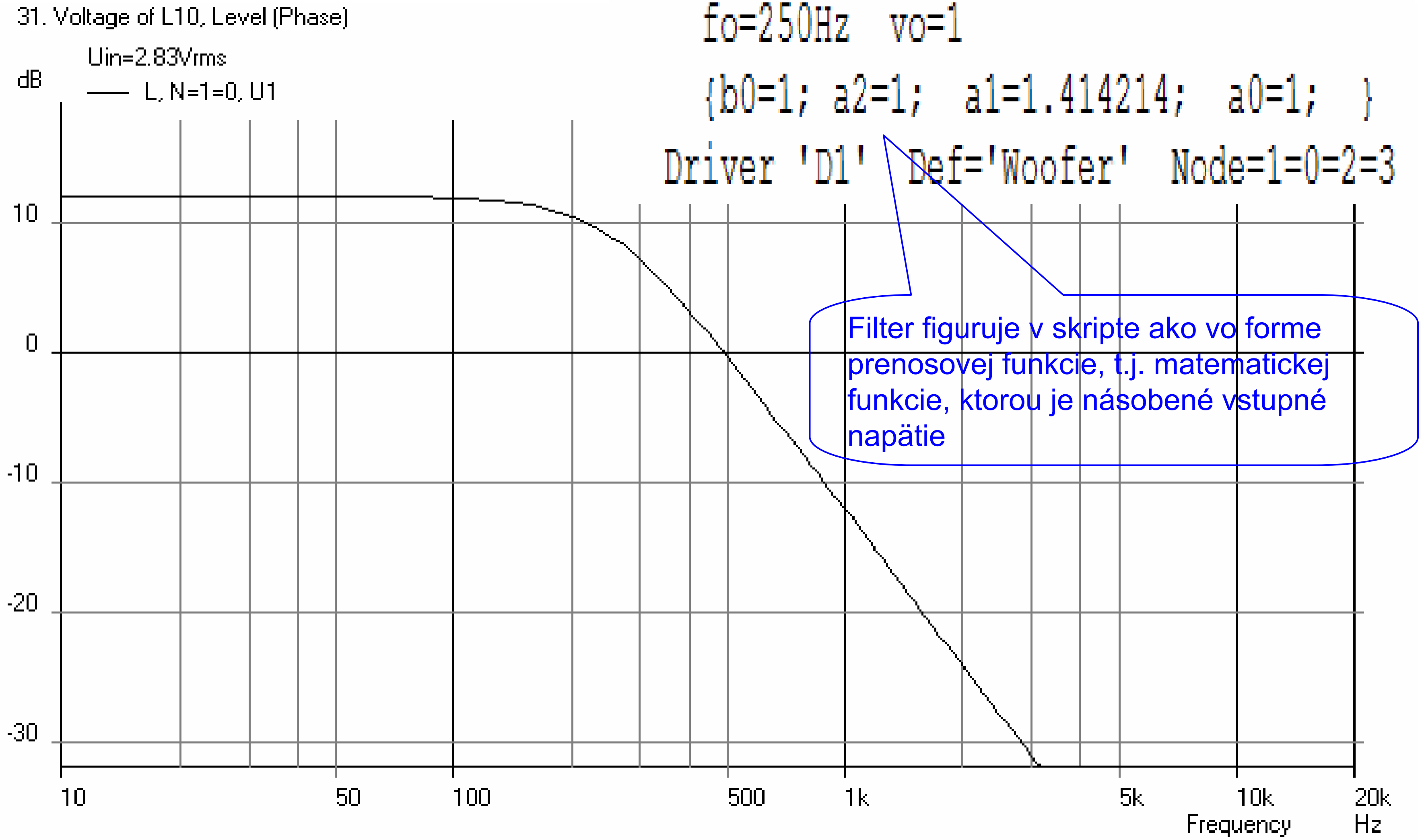
○ Bu-LR Compromise Ripple 0 dB

○ Bu-Thomson M 0

AFCH dolnopriepustného filtra

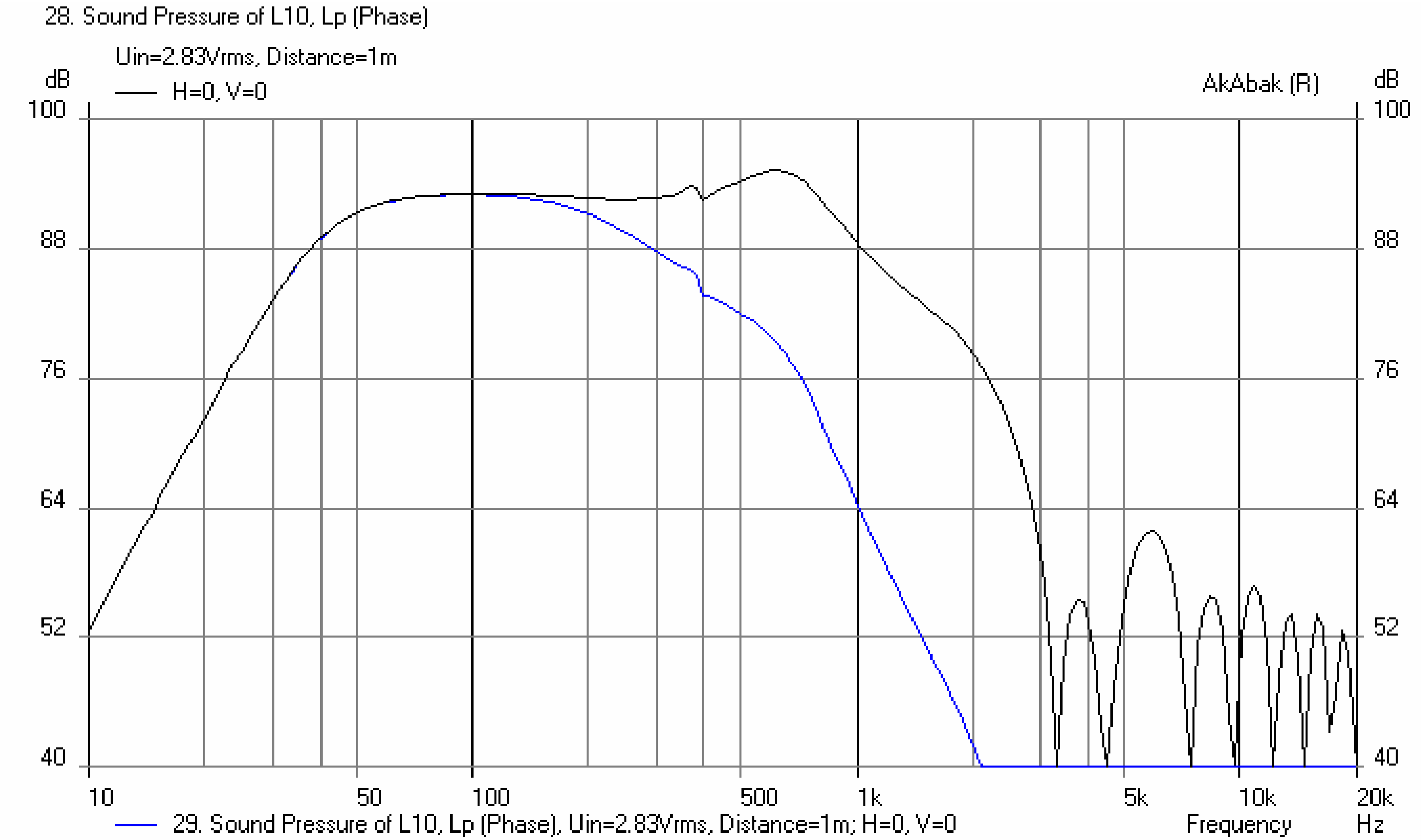
(Butterworthov filter 2. rádu)

```
System 'L'
  Filter    'LPF-B'
    fo=250Hz  vo=1
    {b0=1; a2=1;  a1=1.414214;  a0=1;  }
  Driver 'D1'  Def='Woofer'  Node=1=0=2=3
```



Filter figuruje v skripte ako vo forme prenosovej funkcie, t.j. matematickej funkcie, ktorou je násobené vstupné napätie

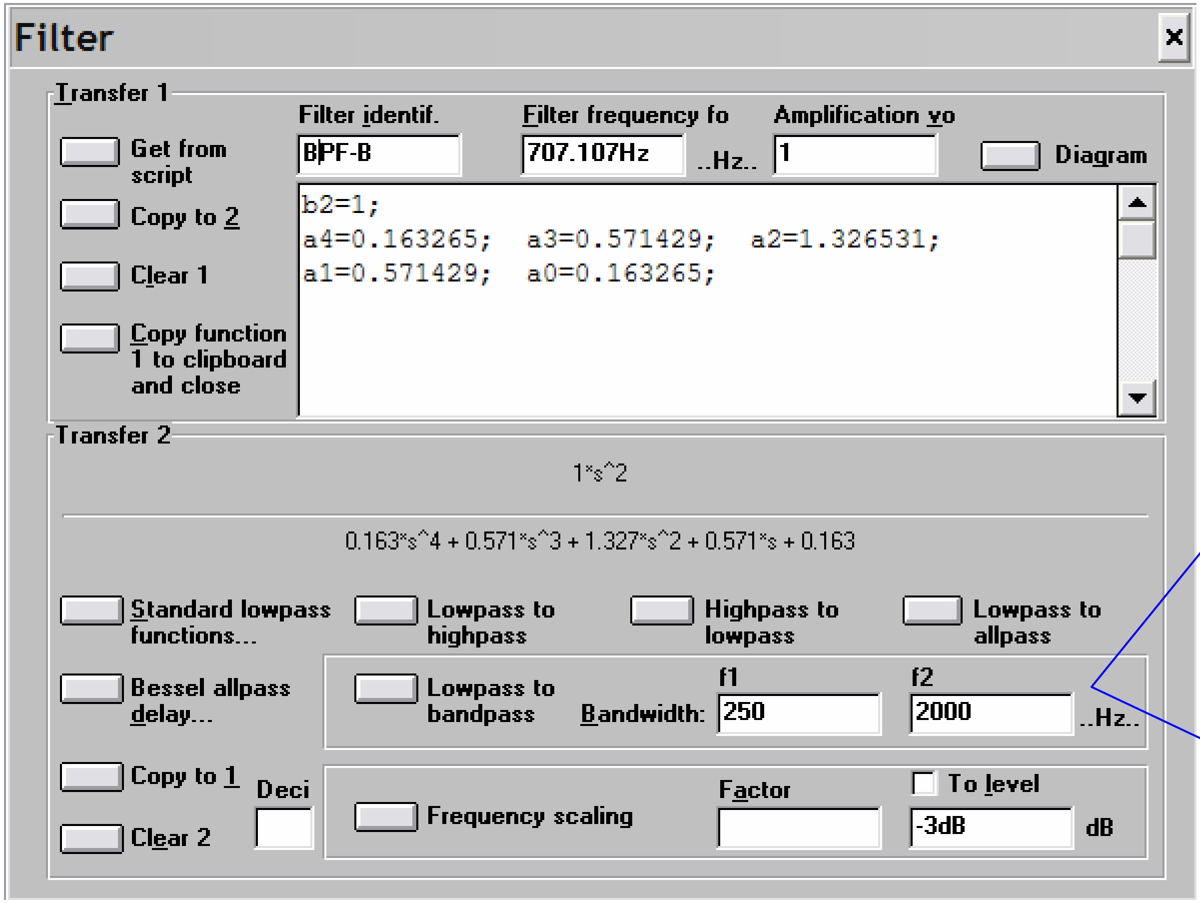
Hladina akustického tlaku nízkotónovej časti pred filtráciou a po filtrácii



Filter-Dialog: Pásmový priepust

(Butterworth, 4. rád)

$$H(s)=\frac{s_0^{\ 2}}{0.163s_0^{\ 4}+0.571s_0^{\ 3}+1.327s_0^{\ 2}+0.571s_0+1}\qquad s_0=\frac{s}{\omega_0}$$



Filter identif.: BPF-B

Filter frequency fo: 707.107Hz ..Hz..

Amplification vo: 1

```
b2=1;
a4=0.163265;  a3=0.571429;  a2=1.326531;
a1=0.571429;  a0=0.163265;
```

$$\frac{1*s\hat{}2}{0.163*s\hat{}4+0.571*s\hat{}3+1.327*s\hat{}2+0.571*s+0.163}$$

Bandwidth: f1 250 f2 2000 ..Hz..

Deci

Factor

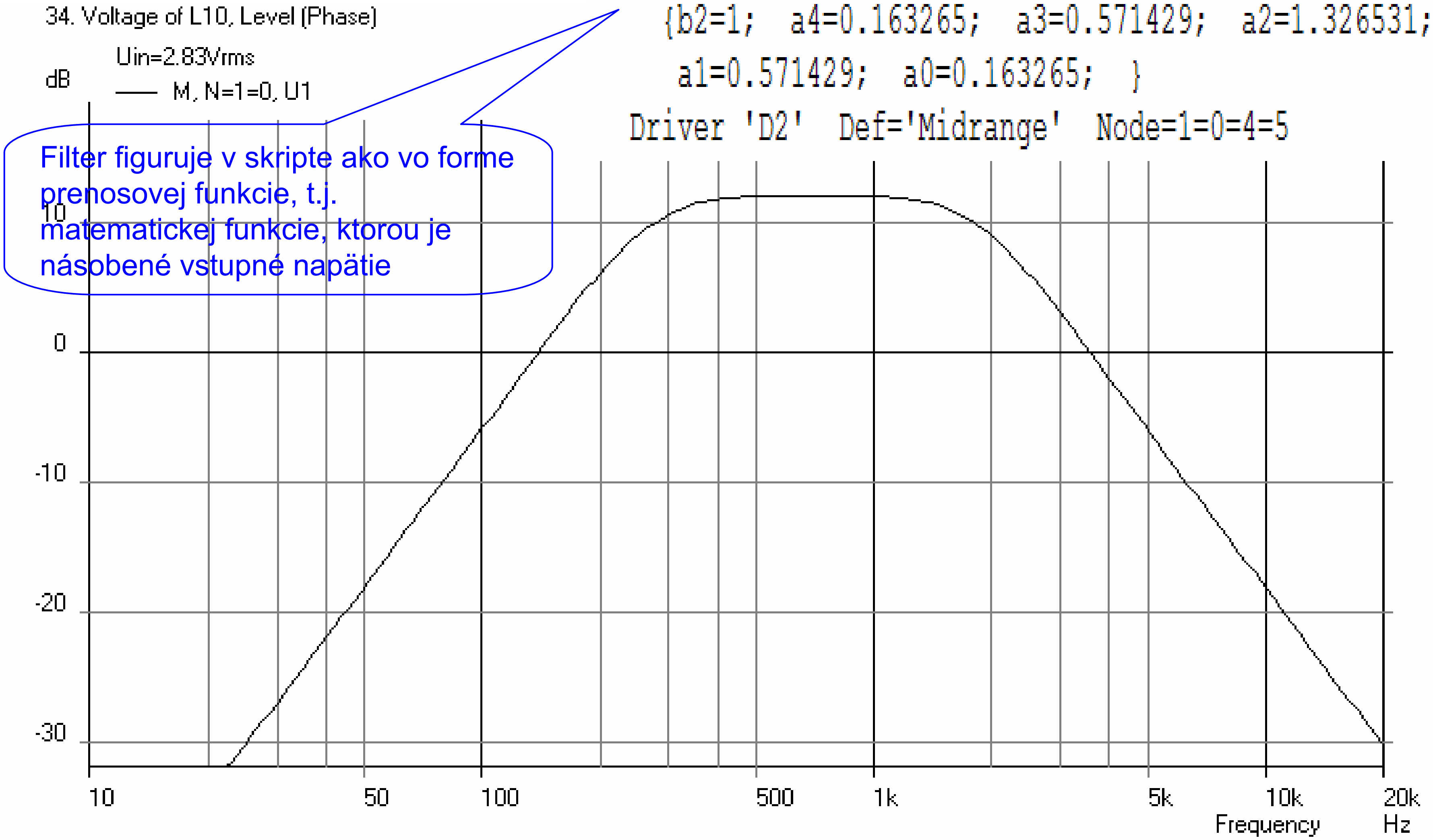
☐ To level -3dB dB

1. Standard Lowpass Functions
2. Výber „Order“ a „Class“ filtra
3. Vložiť „Bandwith“ – frekvencie f1 a f2 (požadované medzné frekvencie pásmového priepustu)
4. Lowpass to bandpass
5. Copy to 1
6. Vloženie „Filter identif.“ a „Amplification“ (filter frequency f0 je automaticky vypočítaná ako geometrický priemer frekvencií f1 a f2
7. Copy function 1 to clipboard and close

AFCH pásmového priepustu

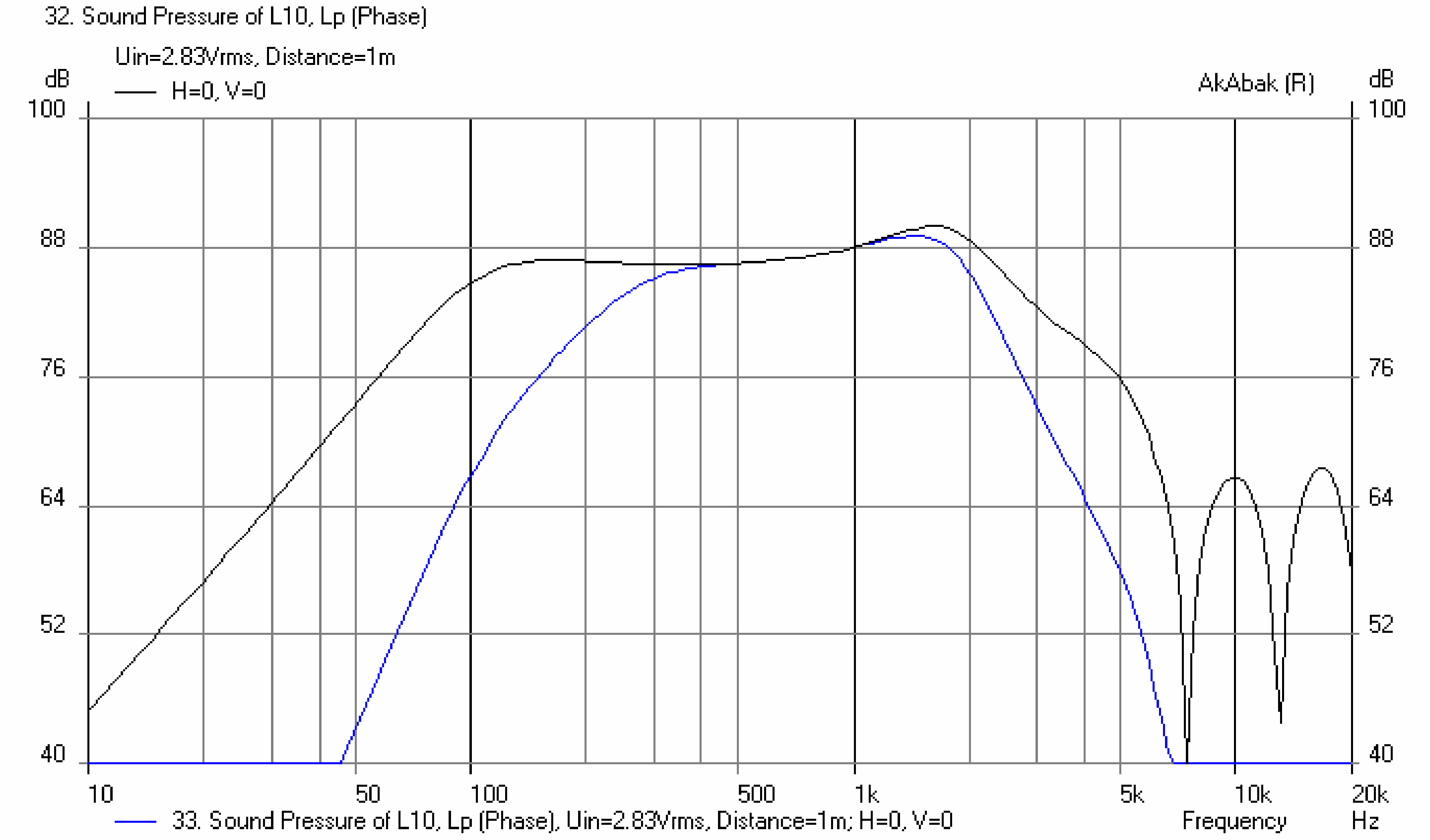
(Butterworthov, 2. rád)

```
System 'M'
  Filter    'BPF-B'
    fo=707.107Hz  vo=1
    {b2=1;  a4=0.163265;  a3=0.571429;  a2=1.326531;
     a1=0.571429;  a0=0.163265;  }
  Driver 'D2'  Def='Midrange'  Node=1=0=4=5
```



Filter figuruje v skripte ako vo forme prenosovej funkcie, t.j. matematickej funkcie, ktorou je násobené vstupné napätie

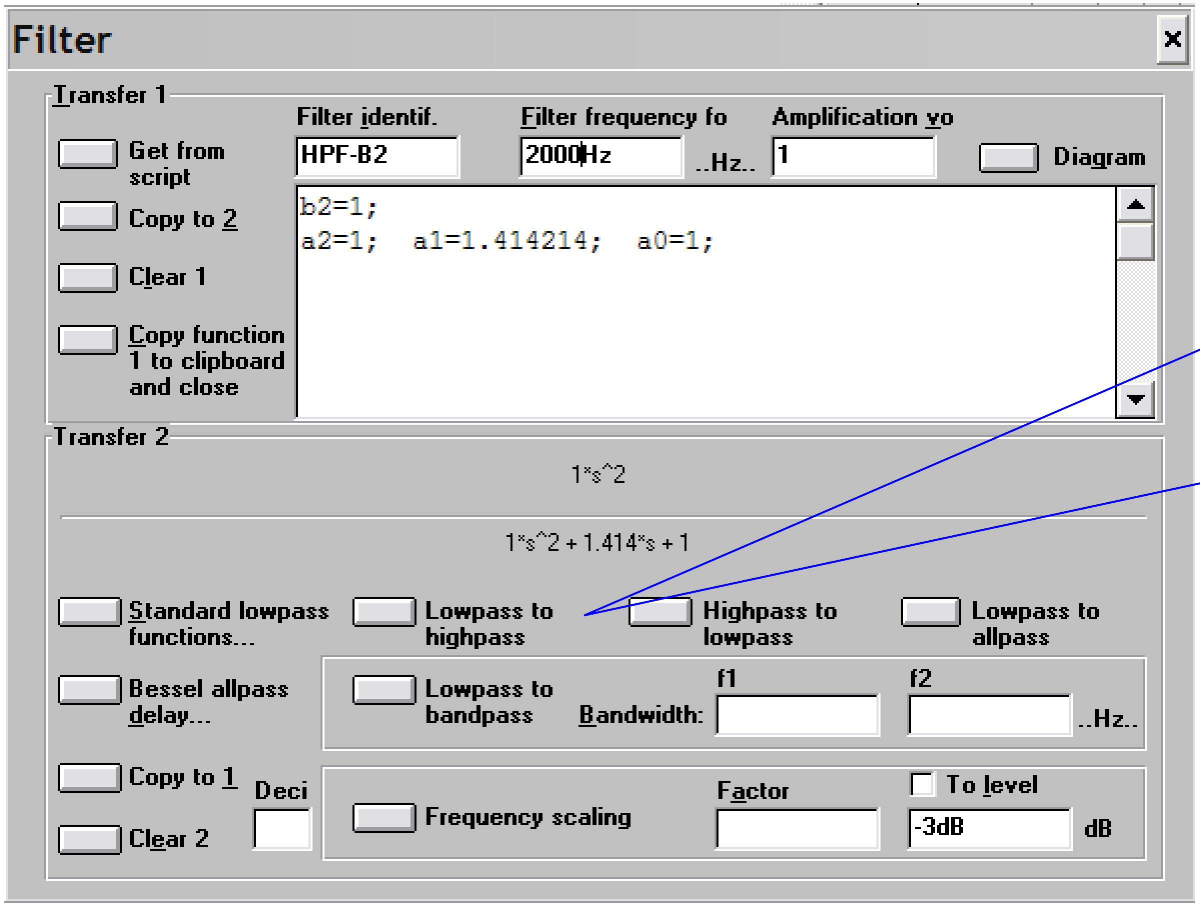
Hladina akustického tlaku stredotónovej časti pred filtráciou a po filtrácii



Filter-Dialog: Hornopriepustný filter (Butterworth, 2. rád)

$$H(s) = \frac{s_0^{\,2}}{s_0^{\,2} + 1.414 s_0 + 1}$$

$$s_0 = \frac{s}{\omega_0}$$



Filter identif.: HPF-B2

Filter frequency fo: 2000Hz ..Hz..

Amplification vo: 1

```
b2=1;
a2=1;   a1=1.414214;   a0=1;
```

1*s^2

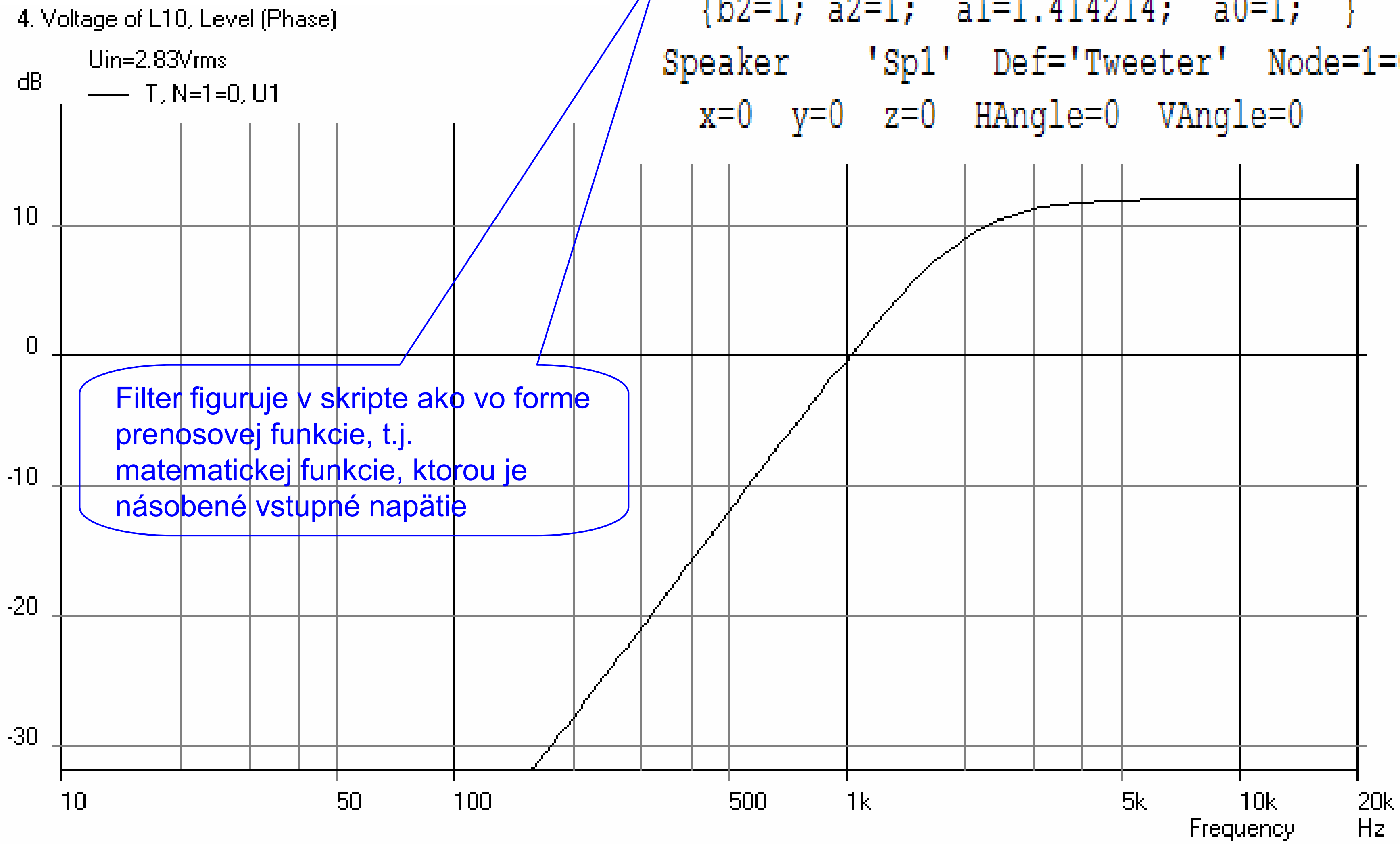
1*s^2 + 1.414*s + 1

To level: -3dB dB

1. Standard Lowpass Functions
2. Výber „Order“ a „Class“ filtra
3. Lowpass to highpass
4. Copy to 1
5. Vloženie „Filter identif.“, „Filter frequency f0“ a „Amplification“
6. Copy function 1 to clipboard and close

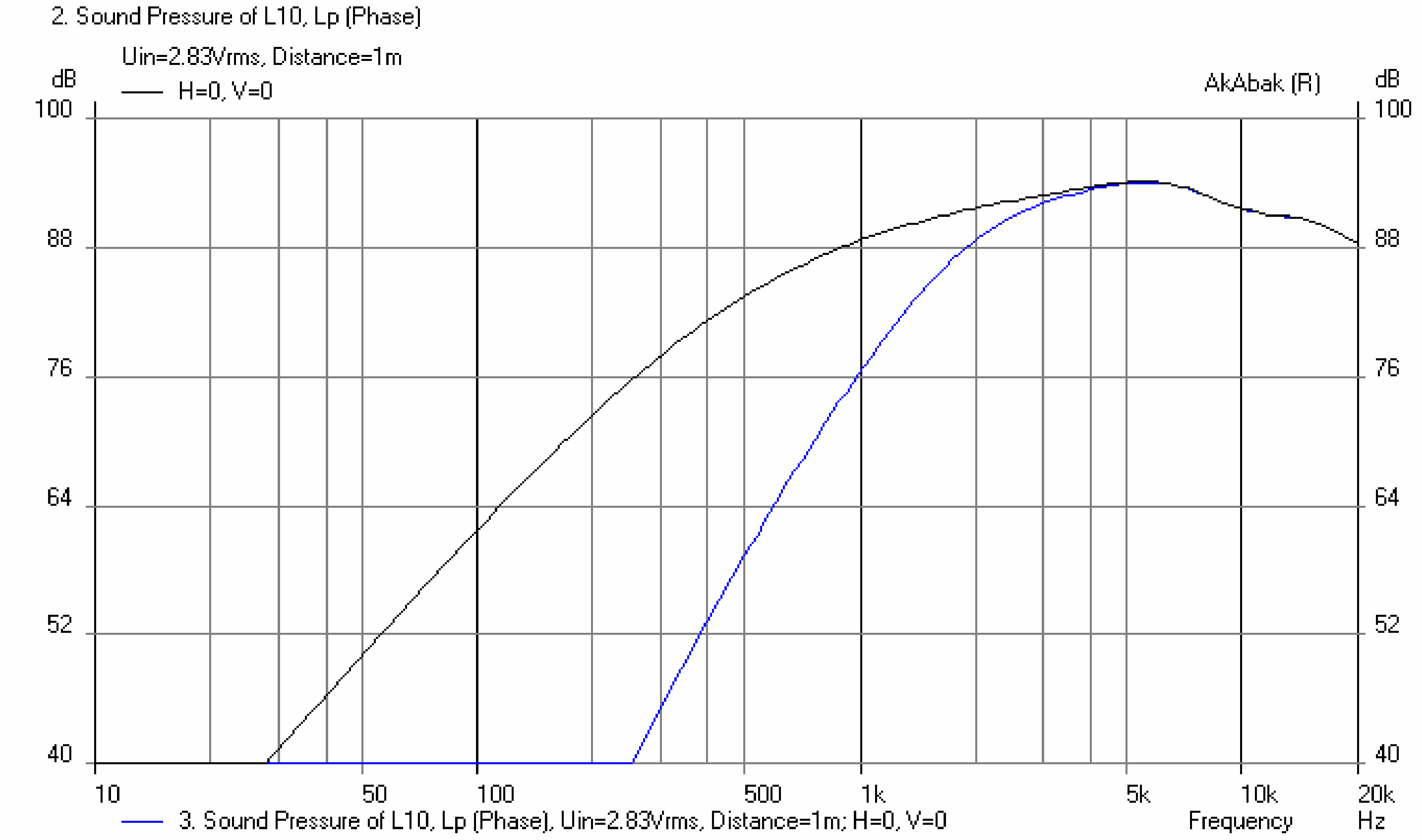
AFCH hornopriepustného filtra
(Butterworthov, 2. rád)

```
System 'T'
  Filter    'HPF-B2'
    fo=2kHz  vo=1
    {b2=1; a2=1;  a1=1.414214;  a0=1;  }
  Speaker    'Sp1'  Def='Tweeter'  Node=1=0
    x=0  y=0  z=0  HAngle=0  VAngle=0
```



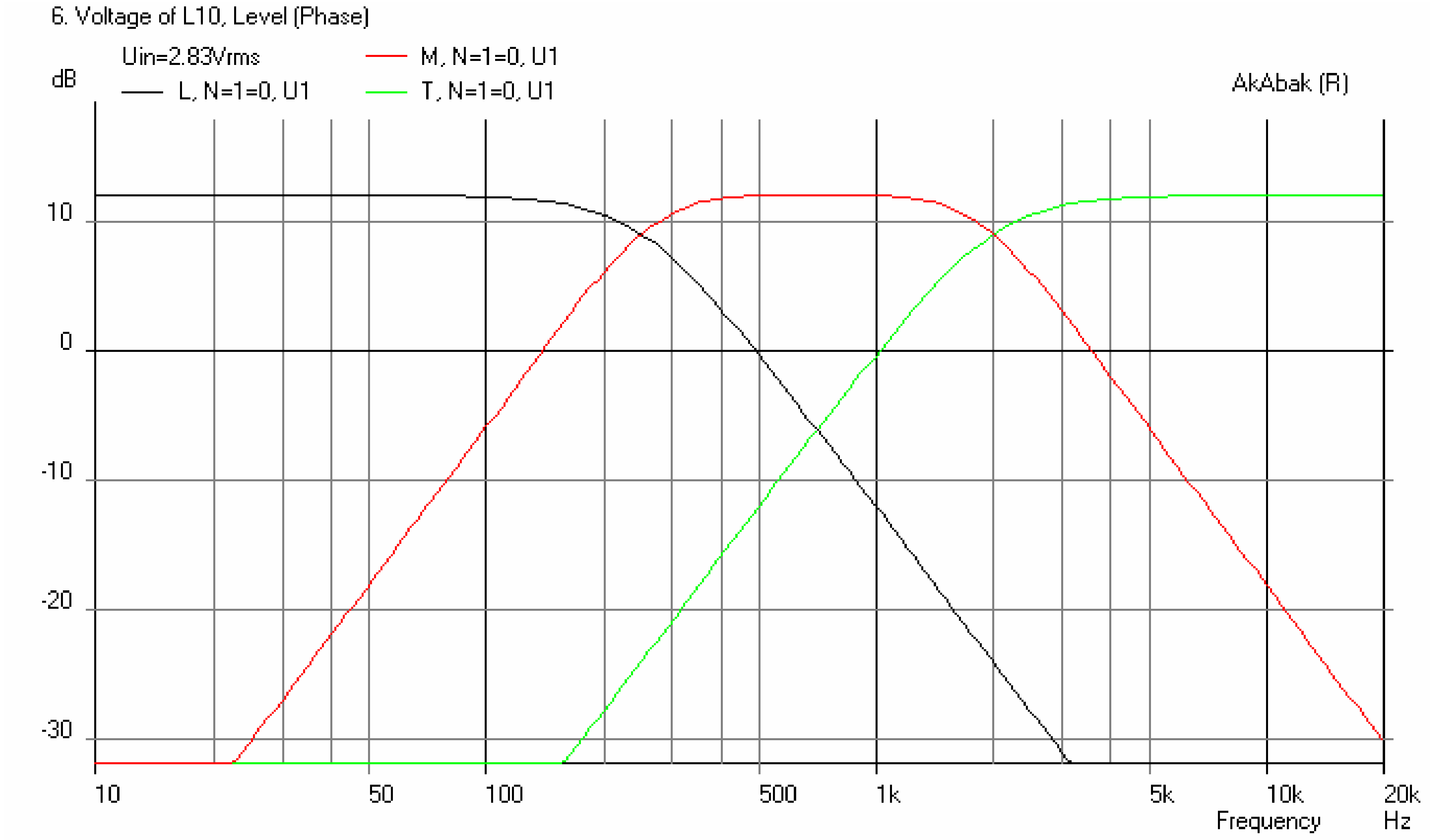
Filter figuruje v skripte ako vo forme prenosovej funkcie, t.j. matematickej funkcie, ktorou je násobené vstupné napätie

Hladina akustického tlaku vysokotónovej časti pred filtráciou a po filtrácii

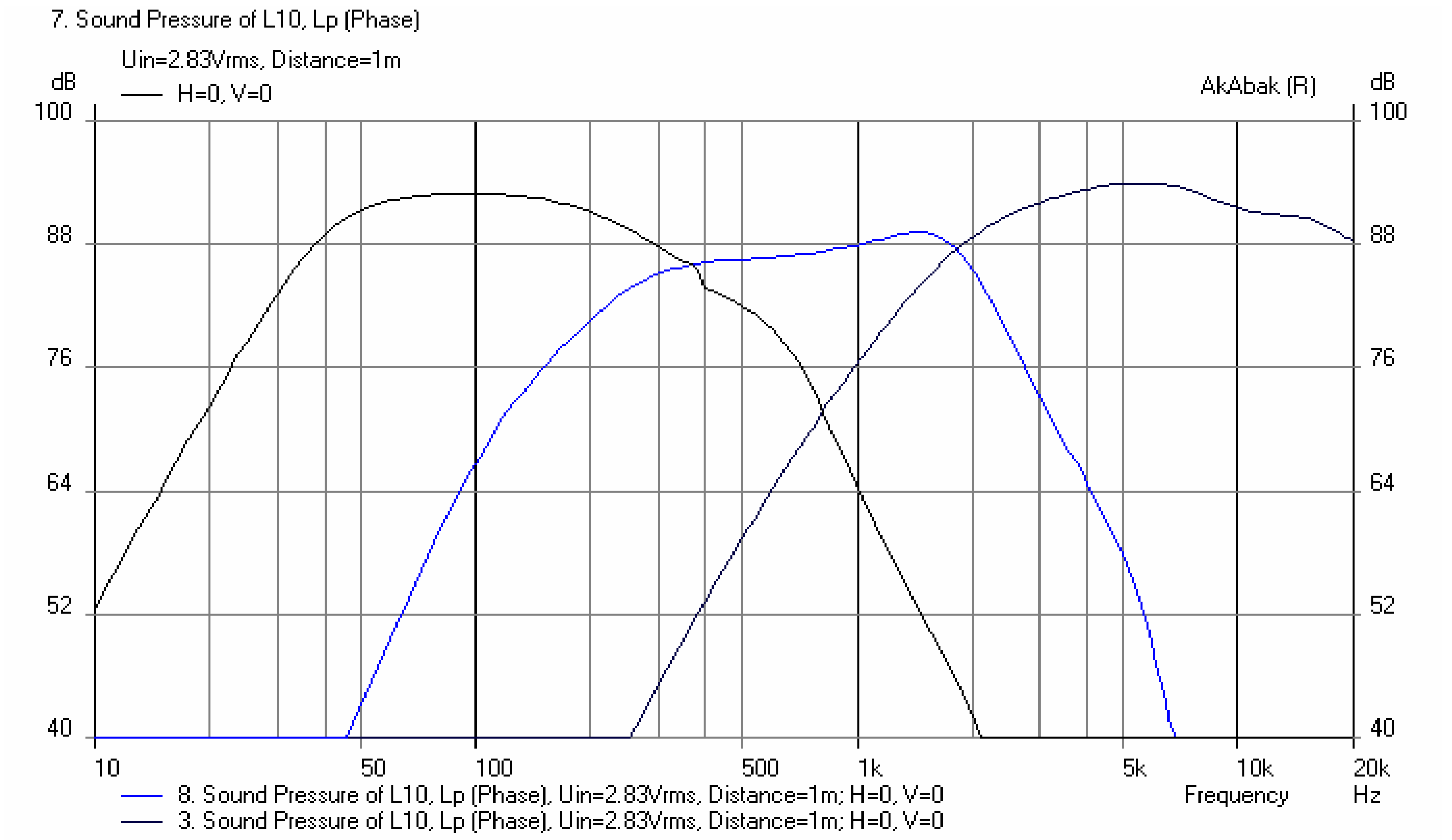


AFCH dolnopriepustného filtra, pásmového priepustu a hornopriepustného filtra: porovnanie

(Butterworth, 2. rád)

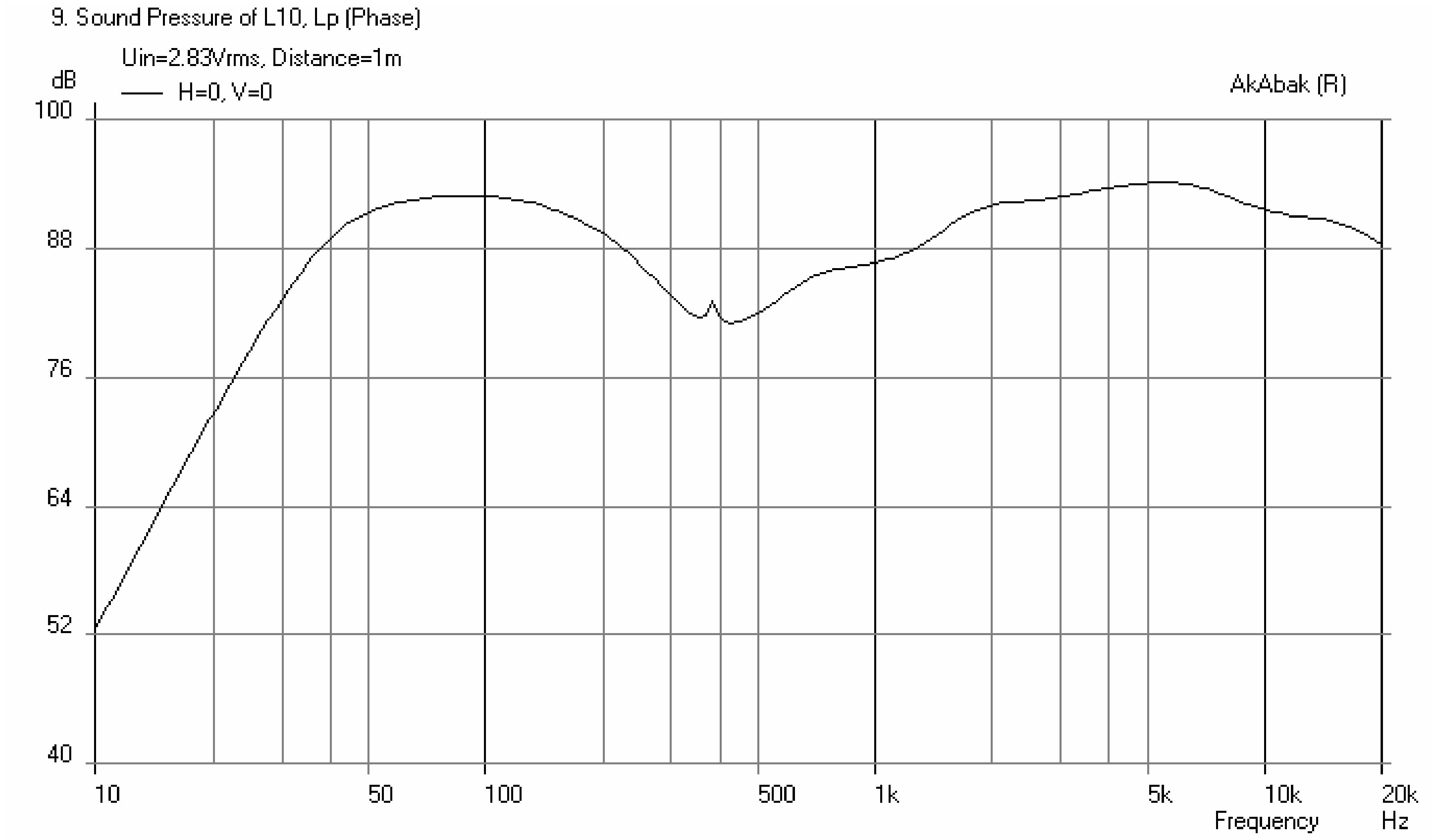


Hladiny akustických tlakov nízkotónovej, stredotónovej a vysokotónovej po filtrácii: porovnanie



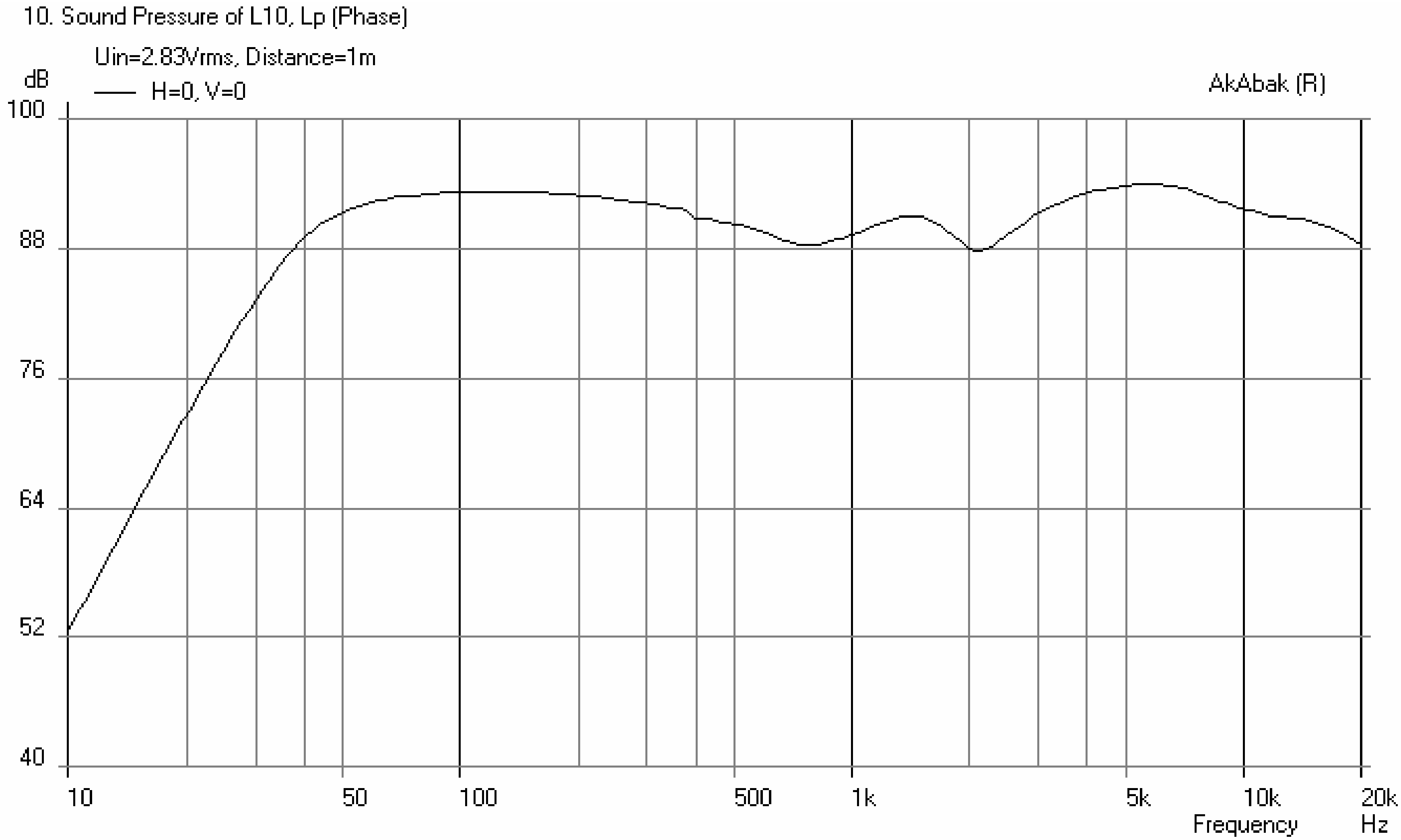
Celková hladina akustického tlaku s použitím elektrických filtrov

(súčet akustických tlakov nízkotónovej, stredotónovej a vysokotónovej)

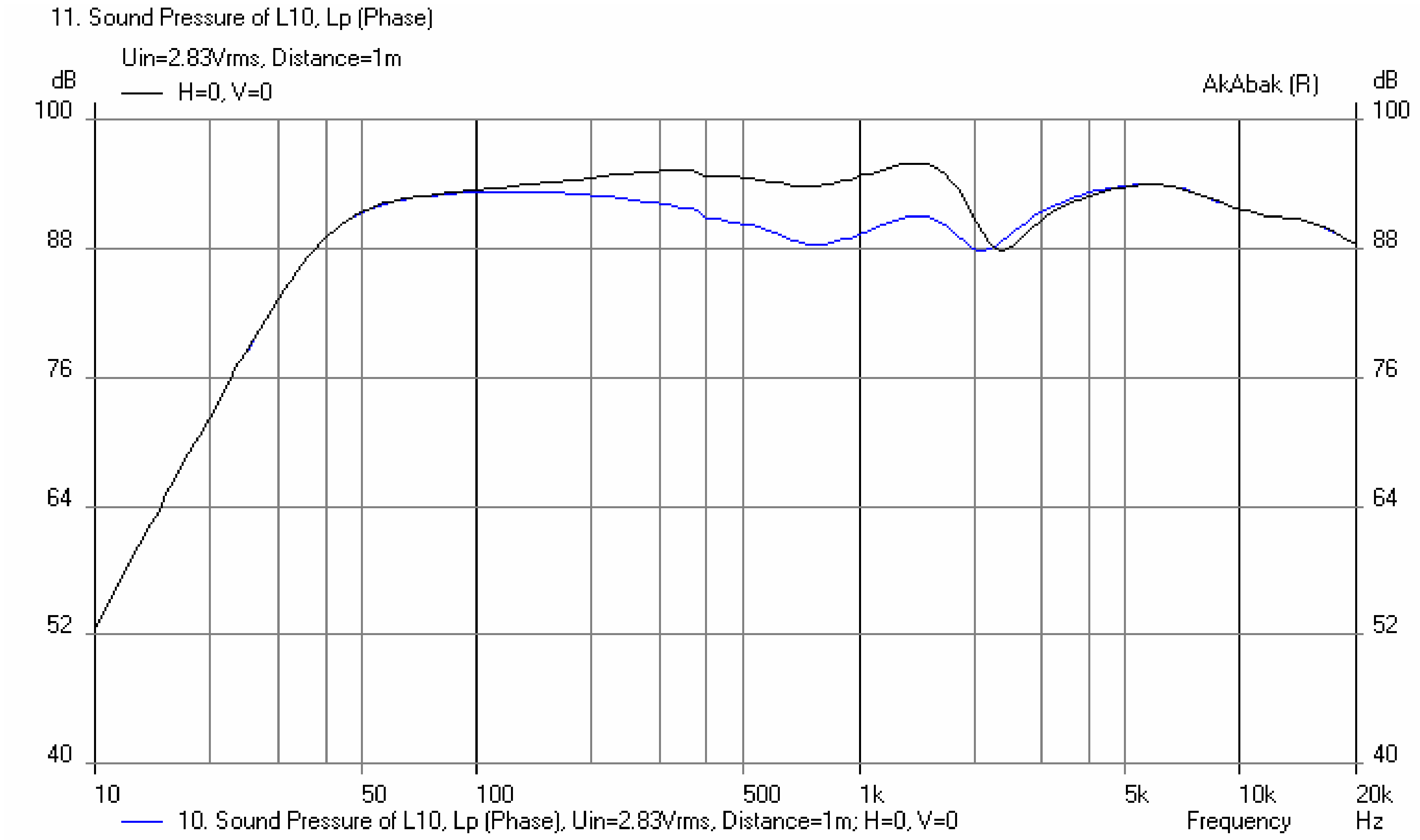


Celková hladina akustického tlaku s použitím elektrických filtrov

(súčet akustických tlakov nízkotónovej, stredotónovej a vysokotónovej, opačná polarita stredotónového reproduktora)



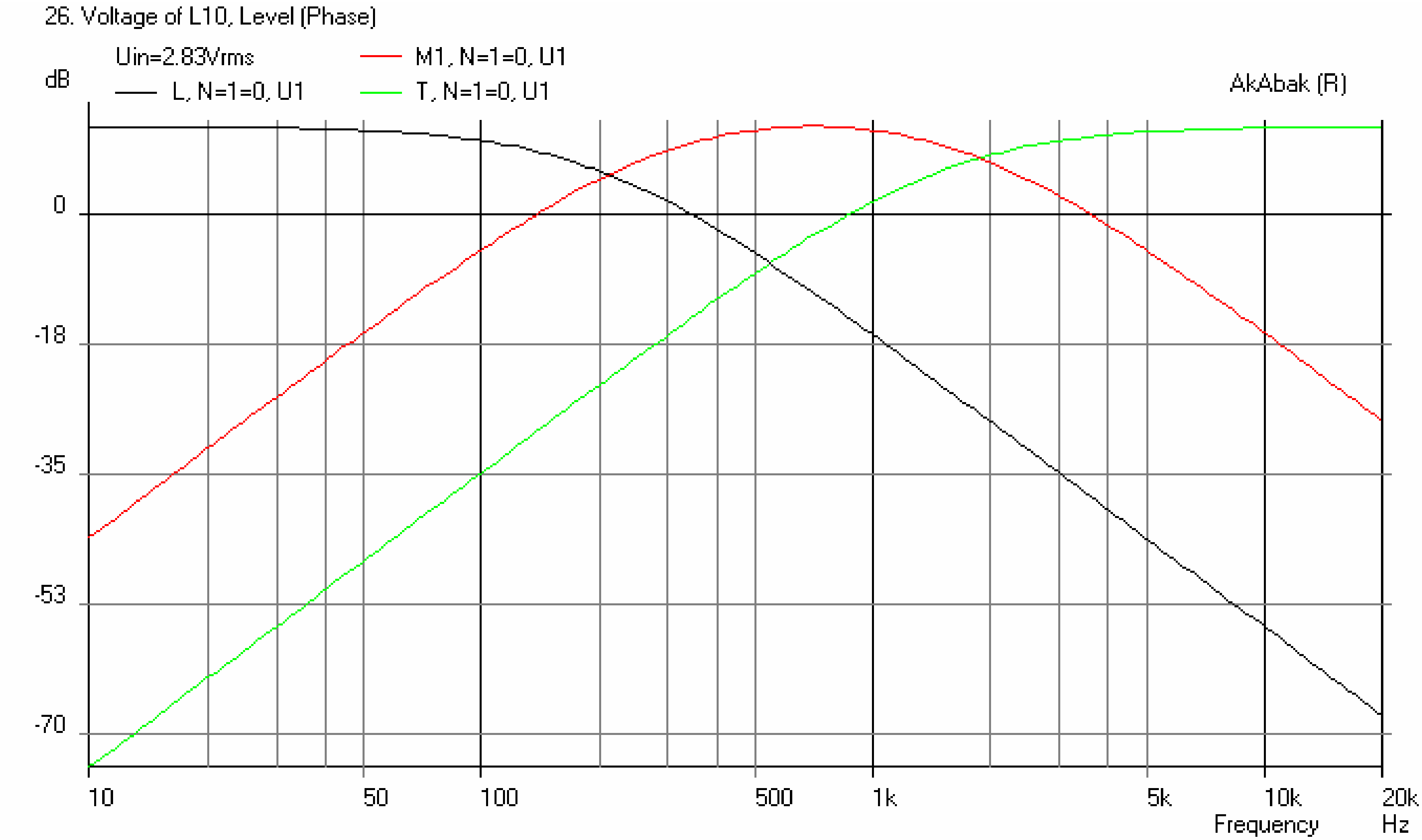
Pridaný ďalší stredotónový reproduktor – zvýšenie citlivosti na stredných frekvenciách



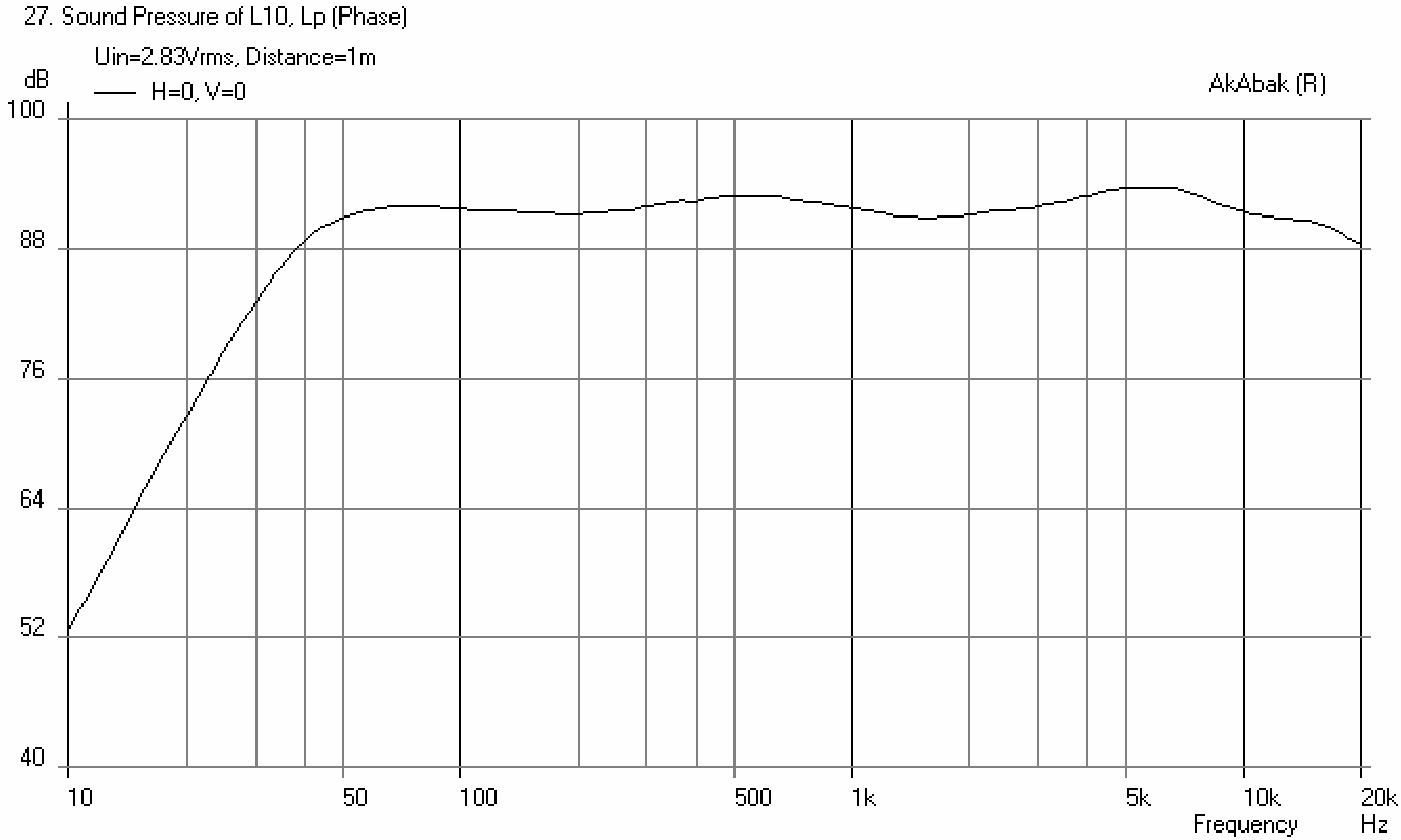
Skript (zmena triedy filtrov na Linwitz-Riley, malá úprava medzných frekvencií)

```
Def_Driver  'Woofer'
 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

Def_Driver  'Midrange'
 SD=55cm2  dD1=3.6cm  tD1=1.75cm   |Cone
 fs=68Hz  Vas=5L  Qms=2.42
 Qes=0.74  Re=6.2ohm  Le=0.31mH  ExpoLe=0.618

Def_Speaker  'Tweeter'
 Meas_Dipole
 SD=7.5cm2  tD1=5.5mm t1=3.5mm  |Convex Dome
 fs=550Hz  Vas=17.8cm3  Qms=2.425
 Bl=3.5Tm  Re=4.8ohm  Le=50uH  ExpoLe=0.618

System 'L'
 Filter   'LPF-LR2'
  fo=200Hz  vo=1
  {b0=1; a2=1;  a1=2;  a0=1;  }
 Driver 'D1'  Def='Woofer'  Node=1=0=2=3
 Radiator  'Rad1'  Def='D1'   Node=2
  x=0  y=0  z=0  HAngle=0  VAngle=0
 Enclosure    'E1'  Node=3
  Vb=45L  Sb=350cm2
  fb=34Hz  dD=10cm  QD/fo=0.34  Visc=0
  x=0  y=0  z=0  HAngle=0  VAngle=0

System 'M1'
 Filter   'BPF-LR2'
  fo=707.106Hz  vo=1
  {b2=1; a4=0.123457;  a3=0.702728;  a2=1.246914;
   a1=0.702728;  a0=0.123457;  }
 Driver 'D2'  Def='Midrange'  Node=0=1=4=5
 Radiator  'Rad1'  Def='D2'   Node=4
  x=0  y=0  z=0  HAngle=0  VAngle=0
 Enclosure    'E2'  Node=5
  Vb=3.2L  Sb=55cm2

System 'M2'
 Filter   'BPF-LR2'
  fo=707.106Hz  vo=1
  {b2=1; a4=0.123457;  a3=0.702728;  a2=1.246914;
   a1=0.702728;  a0=0.123457;  }
 Driver 'D2'  Def='Midrange'  Node=0=1=4=5
 Radiator  'Rad1'  Def='D2'   Node=4
  x=0  y=10cm  z=0  HAngle=0  VAngle=0
 Enclosure    'E2'  Node=5
  Vb=3.2L  Sb=55cm2

System 'T'
 Filter   'HPF-LR2'
  fo=1.5kHz  vo=1
  {b2=1; a2=1;  a1=2;  a0=1;  }
 Speaker    'Sp1'  Def='Tweeter'  Node=0=1
  x=0  y=0  z=0  HAngle=0  VAngle=0
```

AFCH flitrov Linkwitz-Riley 2. rádu



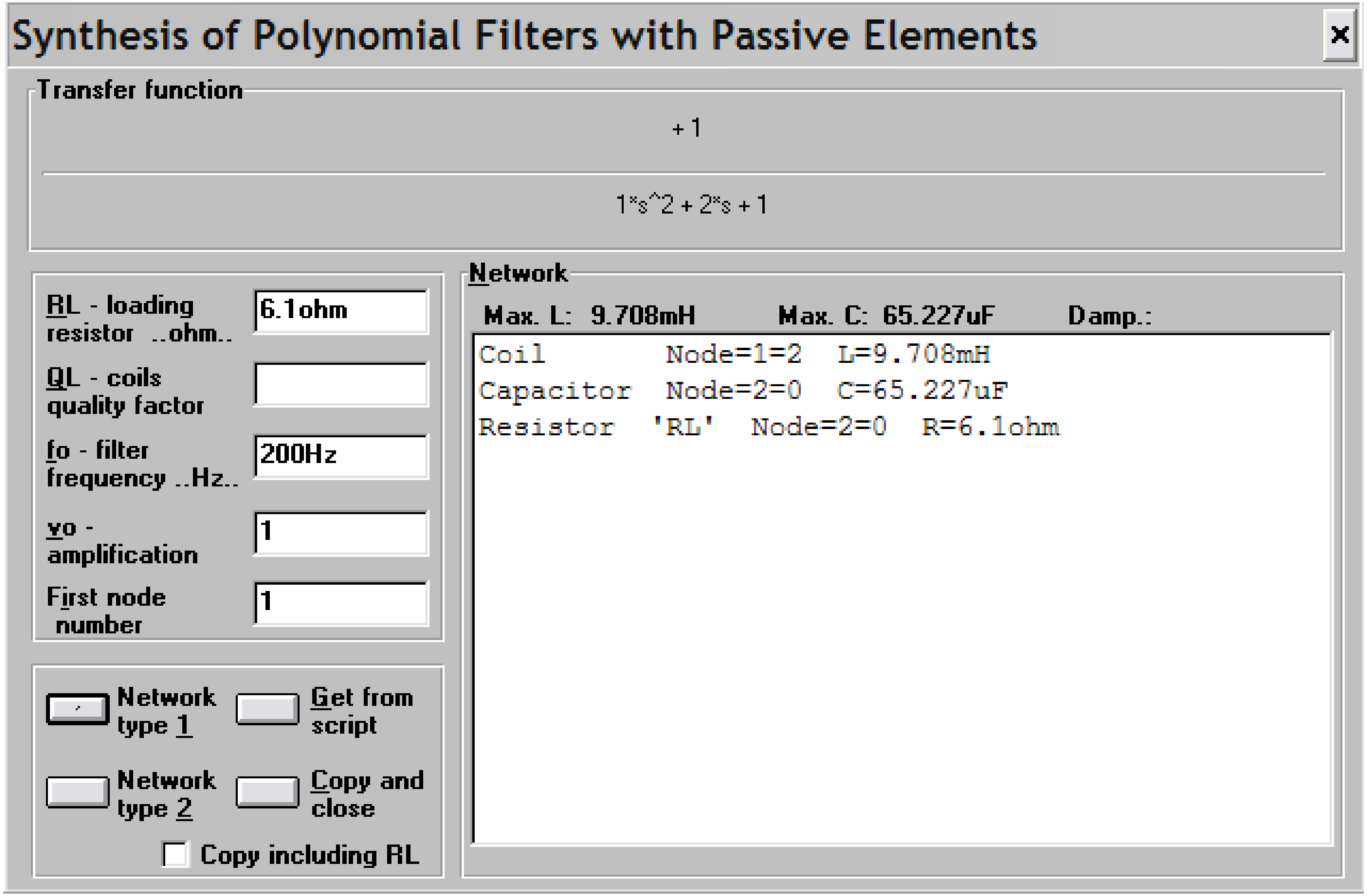
Hladina akustického tlaku sústavy s použitím filtrov triedy Linkwitz-Riley



Syntéza pasívnych filtrov

- …

Syntéza DPF: Filter/LCR-Synthesis



Synthesis of Polynomial Filters with Passive Elements

Transfer function

$$\frac{+1}{1*s^\wedge 2 + 2*s + 1}$$

RL - loading resistor ..ohm..	6.1ohm
QL - coils quality factor	
fo - filter frequency ..Hz..	200Hz
vo - amplification	1
First node number	1

☐ Copy including RL

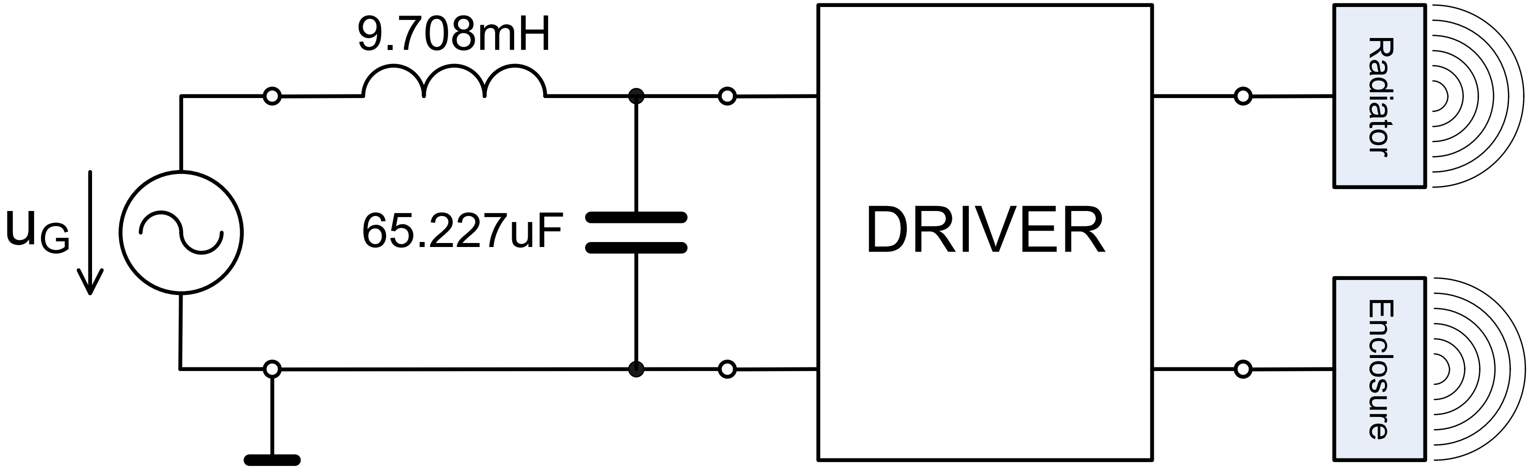
Network

Max. L: 9.708mH Max. C: 65.227uF Damp.:

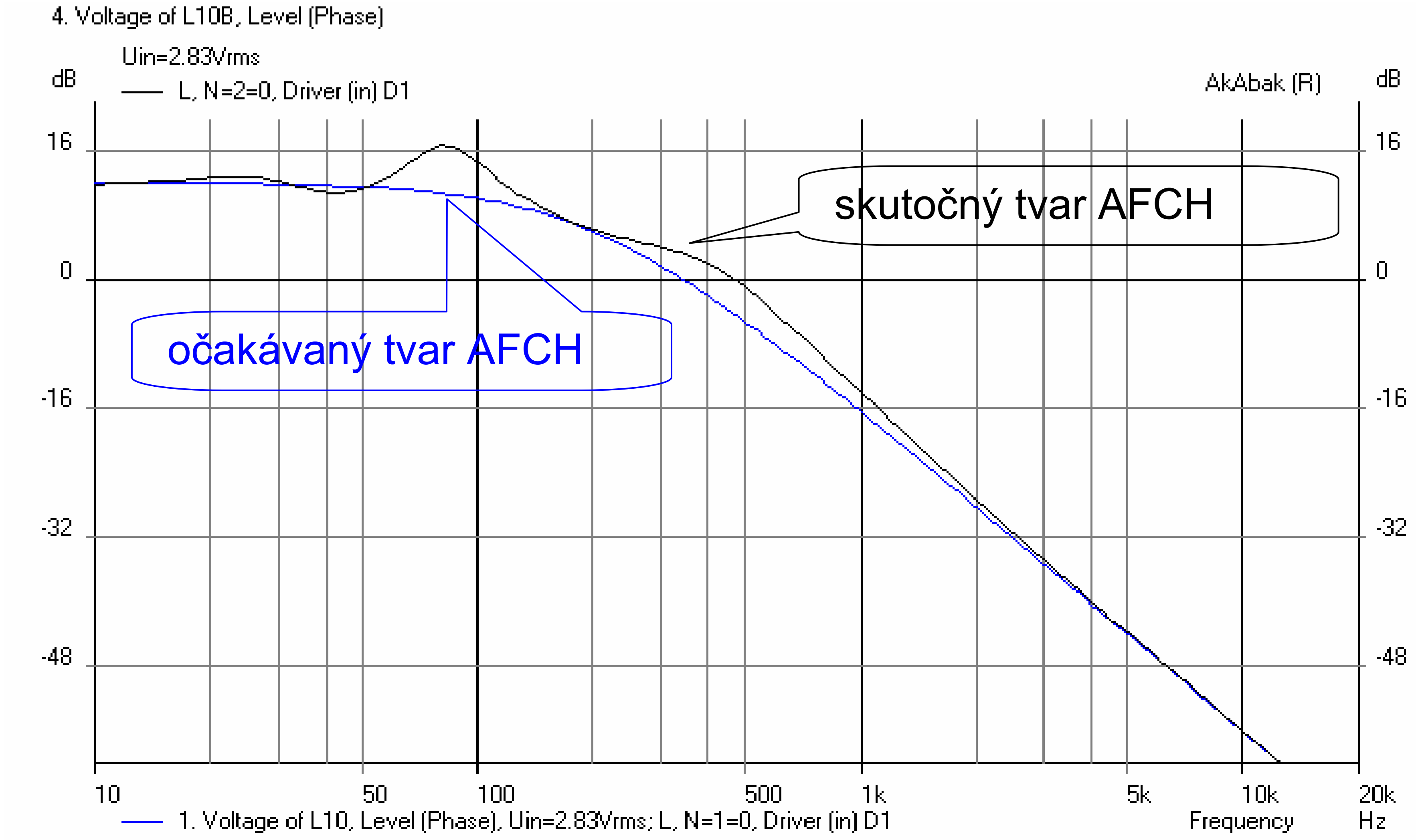
```
Coil         Node=1=2   L=9.708mH
Capacitor    Node=2=0   C=65.227uF
Resistor  'RL'  Node=2=0   R=6.1ohm
```

Nízkotónová časť

```
System 'L'
 Coil      Node=1=2  L=9.708mH
 Capacitor  Node=2=0  C=65.227uF
 SynthesisInfo
  Passive  FirstNode=1  RL=6.1ohm  QL=0
  fo=200Hz  vo=1
  {b0=1;
   a2=1;  a1=2;  a0=1;  }
 Driver 'D1'  Def='Woofer'  Node=2=0=3=4
 Radiator  'Rad1'  Def='D1'    Node=3
  x=0  y=0  z=0  HAngle=0  VAngle=0
 Enclosure   'E1'  Node=4
  Vb=45L  Sb=350cm2
  fb=34Hz  dD=10cm  QD/fo=0.34  Visc=0
  x=0  y=0  z=0  HAngle=0  VAngle=0
```



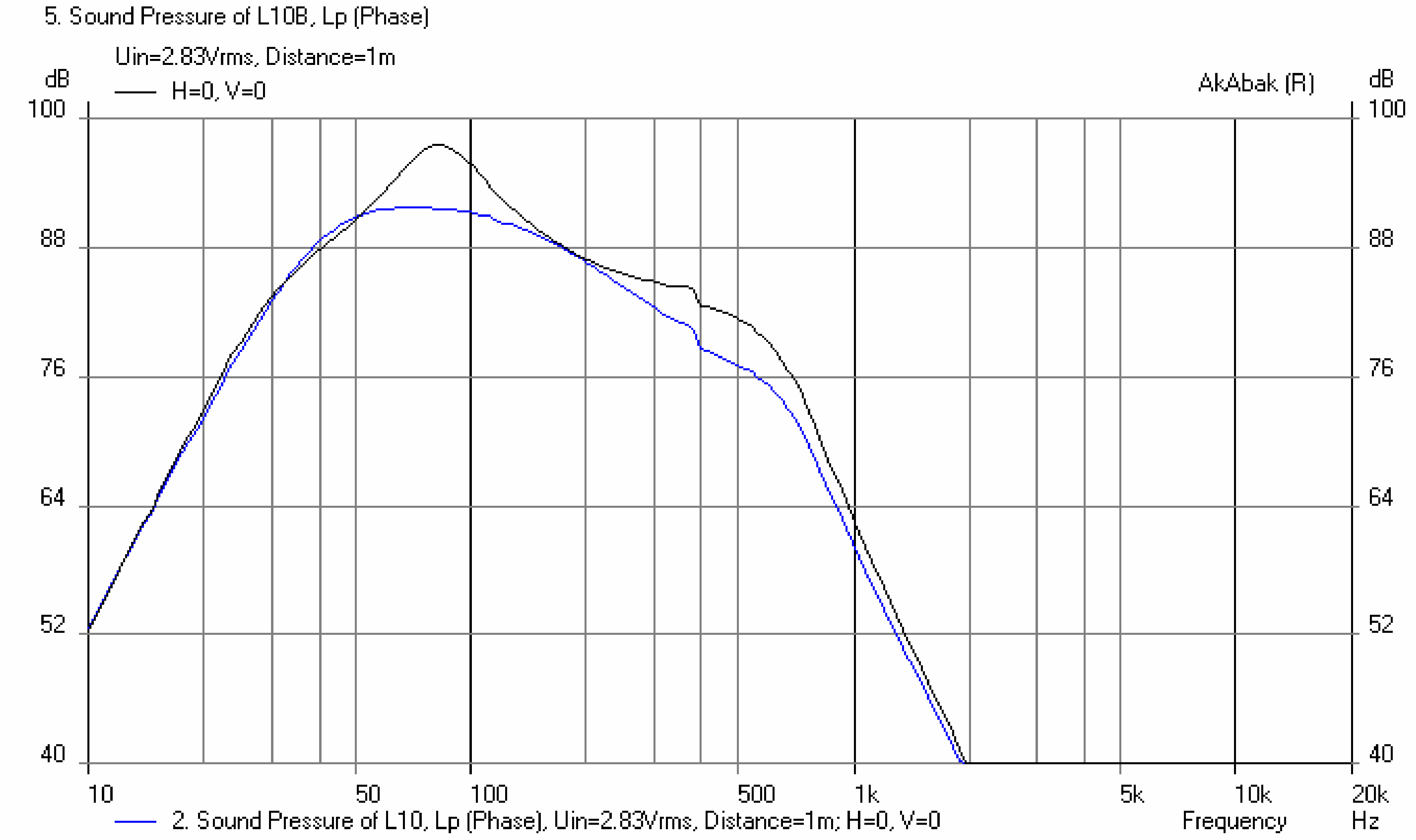
Napätie na výstupe DP filtra: ukážka vplyvu skutočnej impedancie reproduktora na AFCH filtra

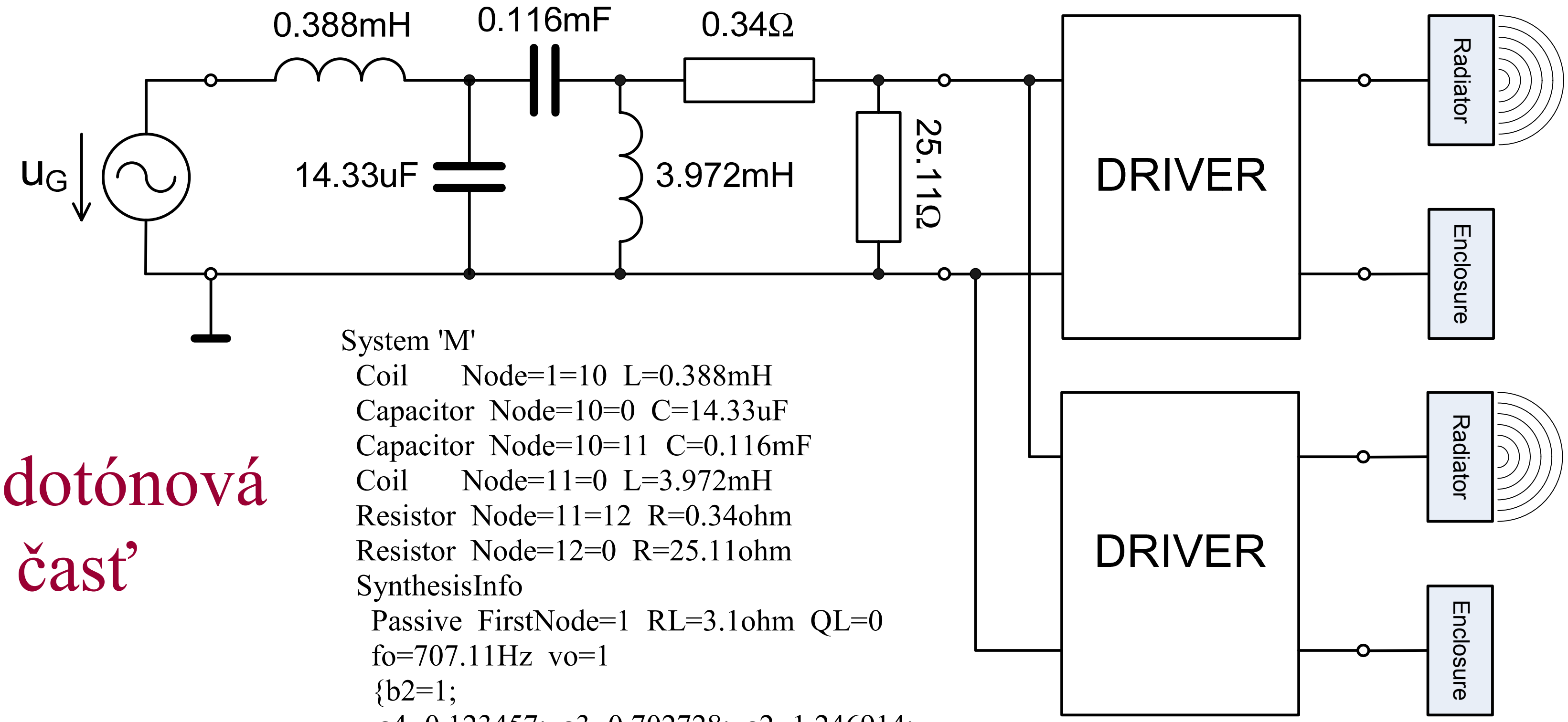


skutočný tvar AFCH

očakávaný tvar AFCH

Hladina akustického tlaku nízkotónovej časti po filtrácii skutočným filtrom (záťažou je impedancia reproduktora)

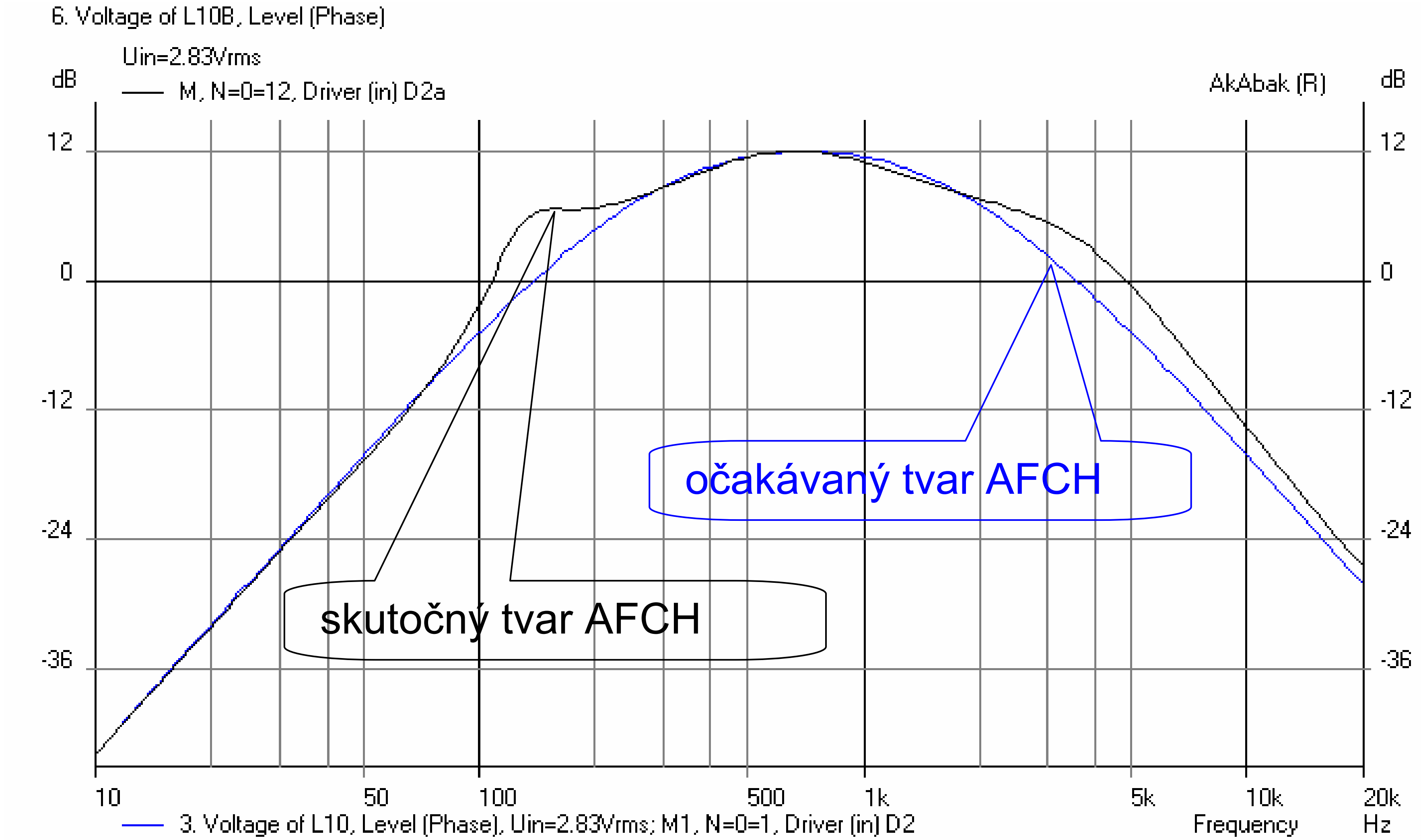




Stredotónová časť

```
System 'M'
 Coil      Node=1=10  L=0.388mH
 Capacitor  Node=10=0  C=14.33uF
 Capacitor  Node=10=11  C=0.116mF
 Coil      Node=11=0  L=3.972mH
 Resistor  Node=11=12  R=0.34ohm
 Resistor  Node=12=0  R=25.11ohm
 SynthesisInfo
  Passive  FirstNode=1  RL=3.1ohm  QL=0
  fo=707.11Hz  vo=1
  {b2=1;
   a4=0.123457;  a3=0.702728;  a2=1.246914;
   a1=0.702728;  a0=0.123457;  }

 Driver 'D2'  Def='Midrange'  Node=0=12=15=16
 Radiator  'Rad1'  Def='D2'   Node=15
  x=0  y=0  z=0  HAngle=0  VAngle=0
 Enclosure    'E2'  Node=16
  Vb=3.2L  Sb=55cm2

 Driver 'D2'  Def='Midrange'  Node=0=12=17=18
 Radiator  'Rad1'  Def='D2'   Node=17
  x=0  y=10cm  z=0  HAngle=0  VAngle=0
 Enclosure    'E2'  Node=18
  Vb=3.2L  Sb=55cm2
```

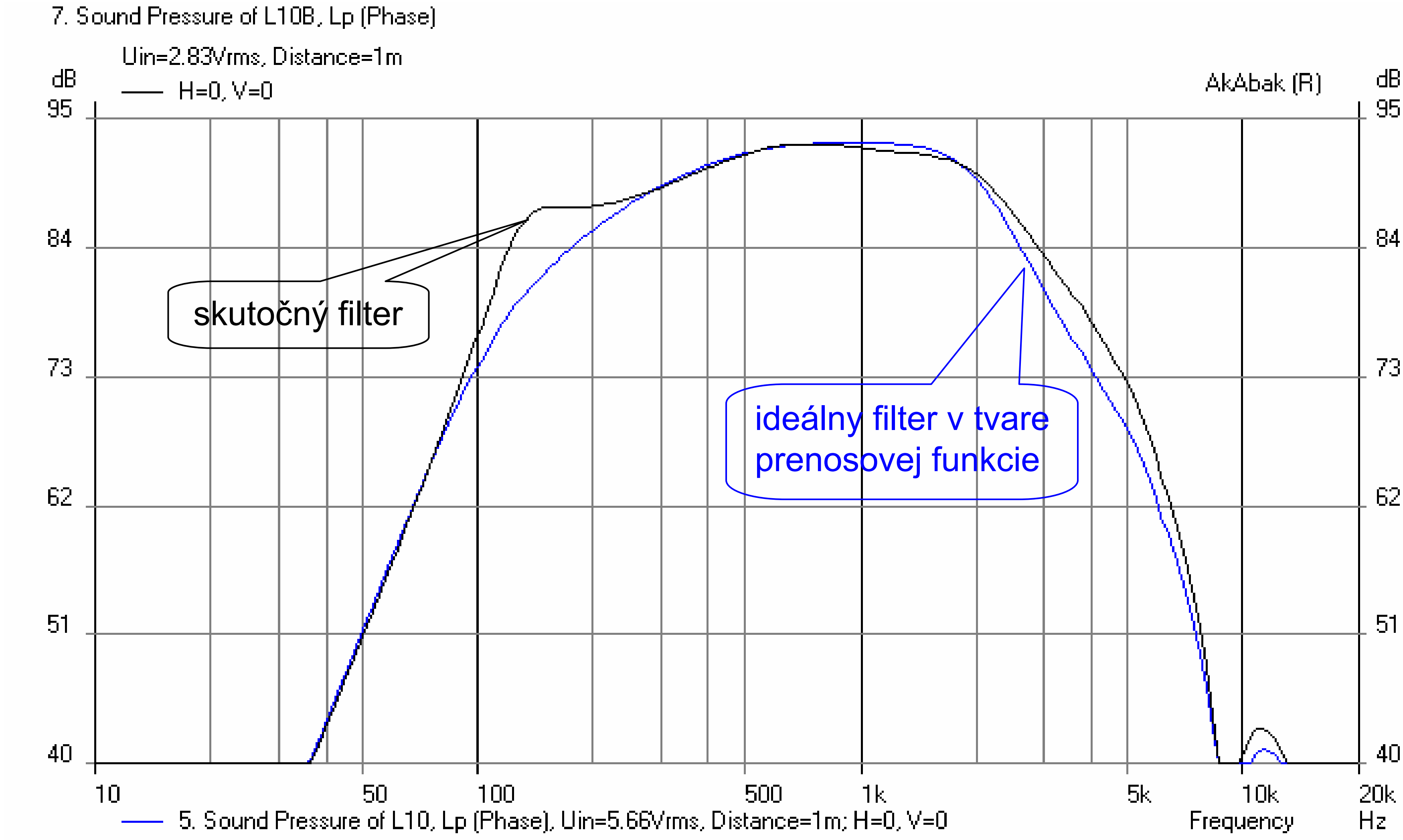
Napätie na výstupe P filtra: ukážka vplyvu skutočnej impedancie reproduktora na AFCH filtra



očakávaný tvar AFCH

skutočný tvar AFCH

Hladina akustického tlaku stredotónovej časti po filtrácii skutočným filtrom (záťažou je impedancia reproduktora)

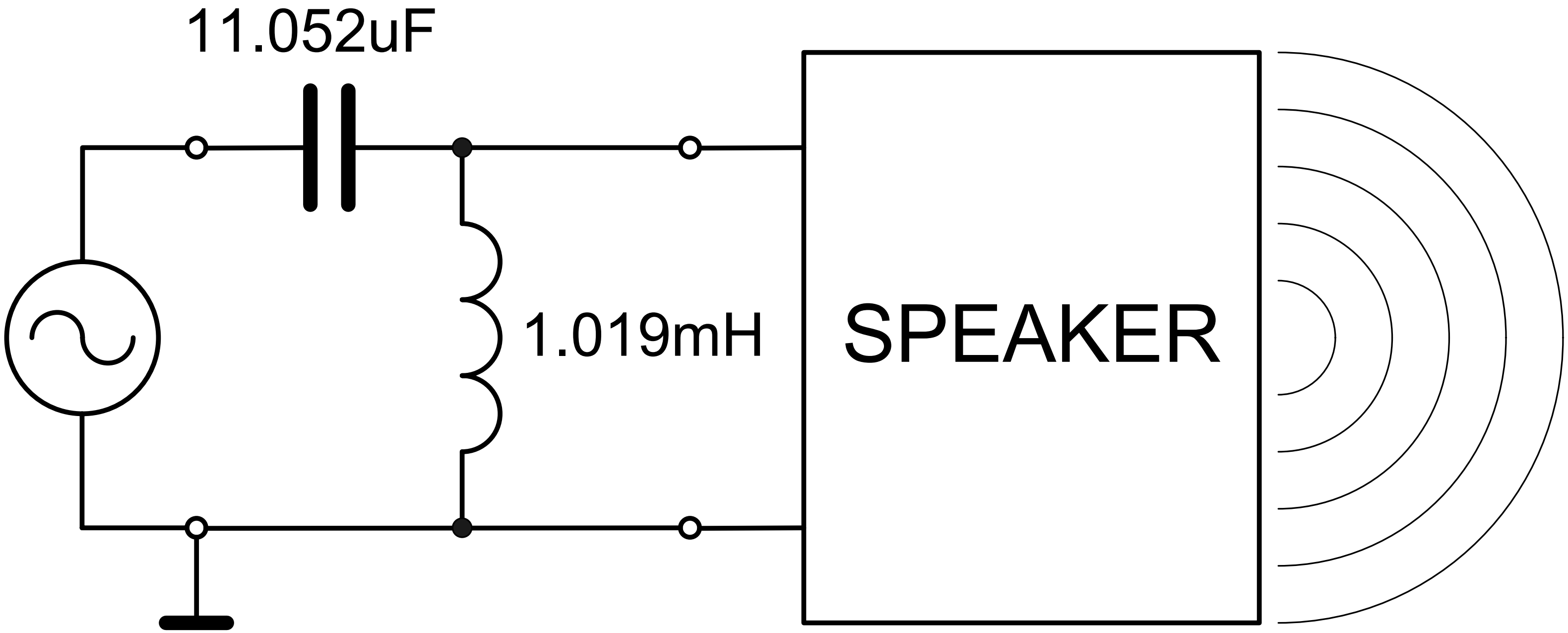


skutočný filter

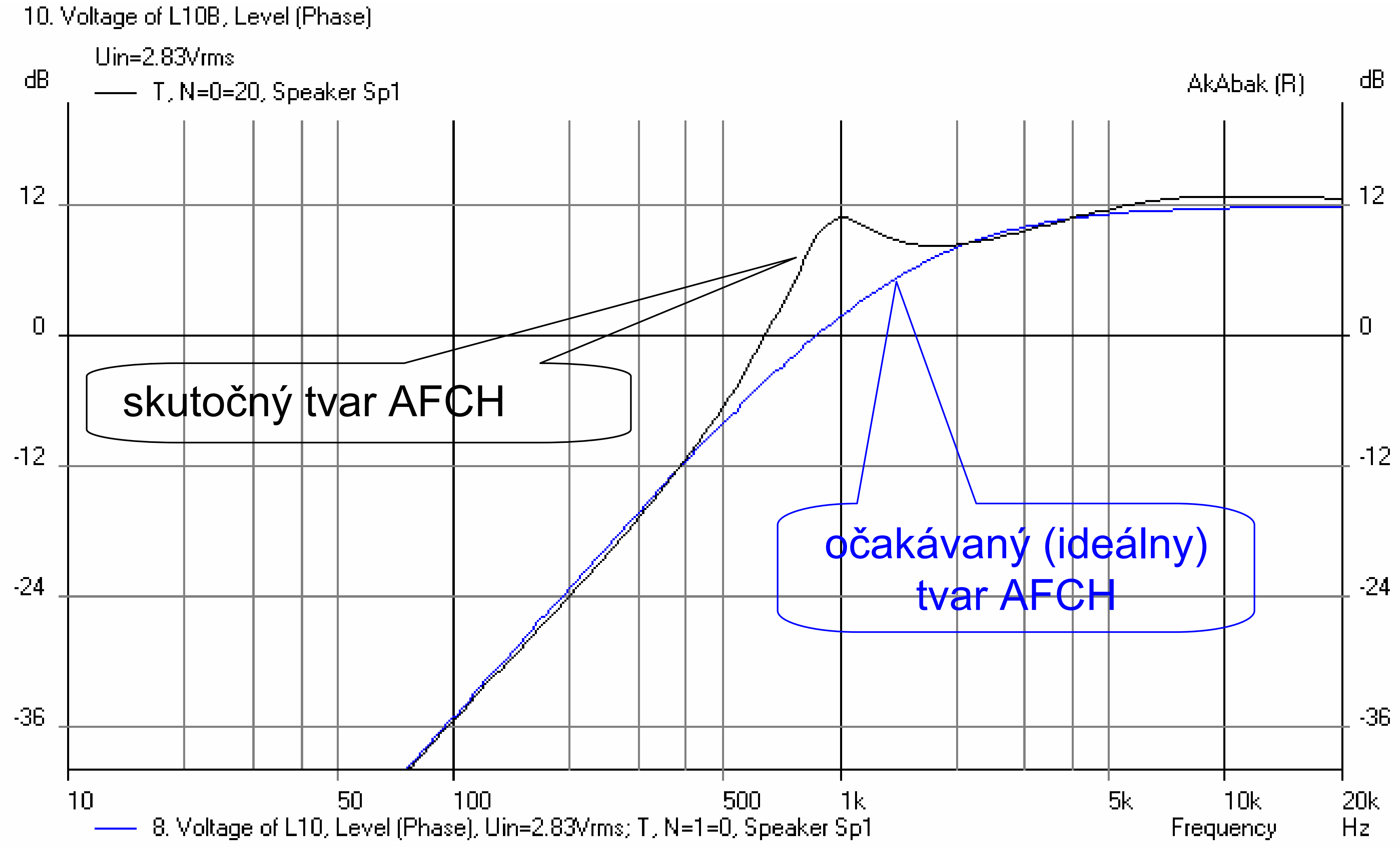
ideálny filter v tvare prenosovej funkcie

Vysokotónová časť

```
System 'T'
  Capacitor  Node=1=20  C=11.052uF
  Coil       Node=20=0  L=1.019mH
  SynthesisInfo
    Passive  FirstNode=1  RL=4.8ohm  QL=0
    fo=1.5kHz  vo=1
    {b2=1;
     a2=1;  a1=2;  a0=1;  }
  Speaker   'Sp1'  Def='Tweeter'  Node=0=20
    x=0  y=0  z=0  HAngle=0  VAngle=0
```



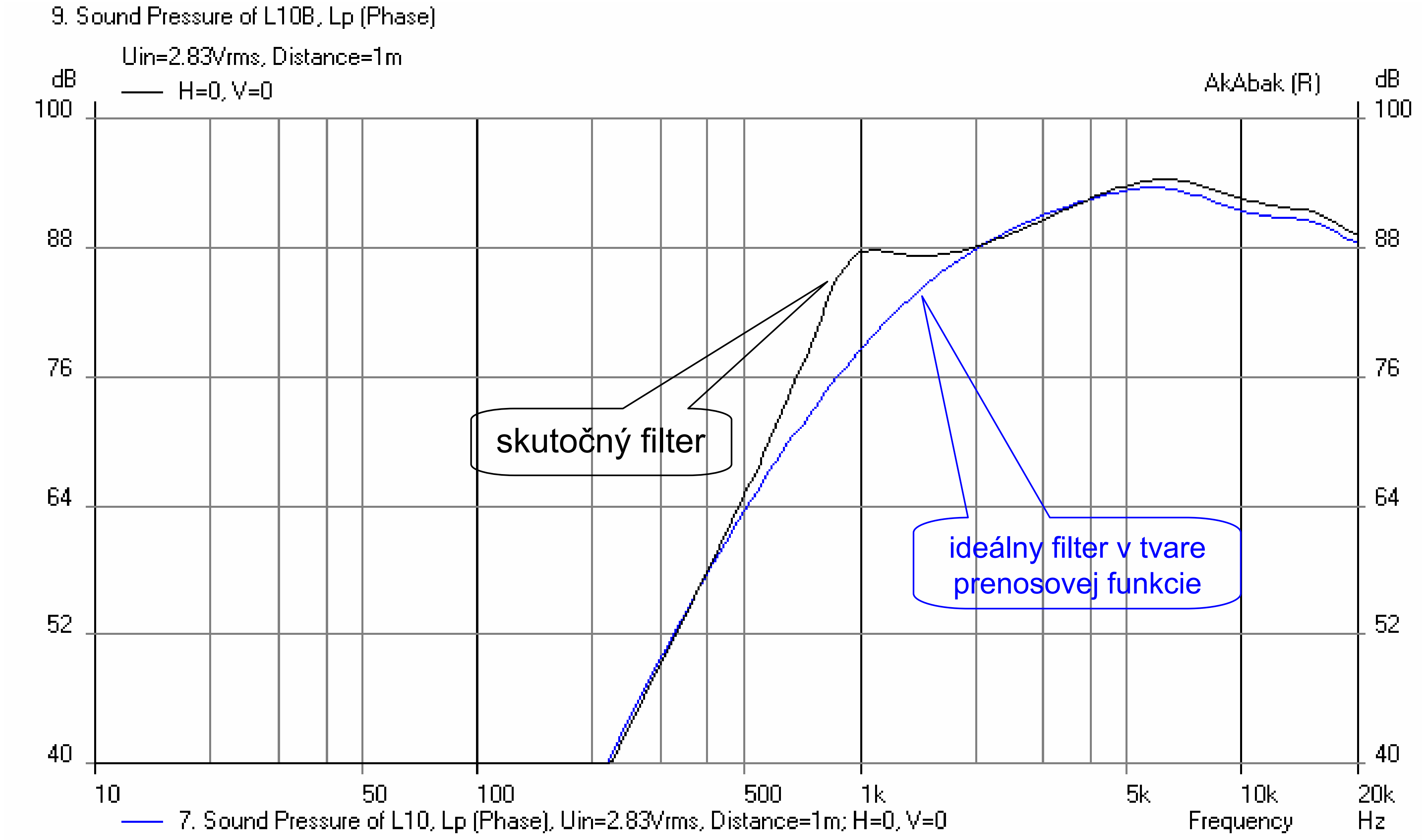
Napätie na výstupe HP filtra: ukážka vplyvu skutočnej impedancie reproduktora na AFCH filtra



skutočný tvar AFCH

očakávaný (ideálny) tvar AFCH

Hladina akustického tlaku vysokotónovej časti po filtrácii skutočným filtrom (záťažou je impedancia reproduktora)



skutočný filter

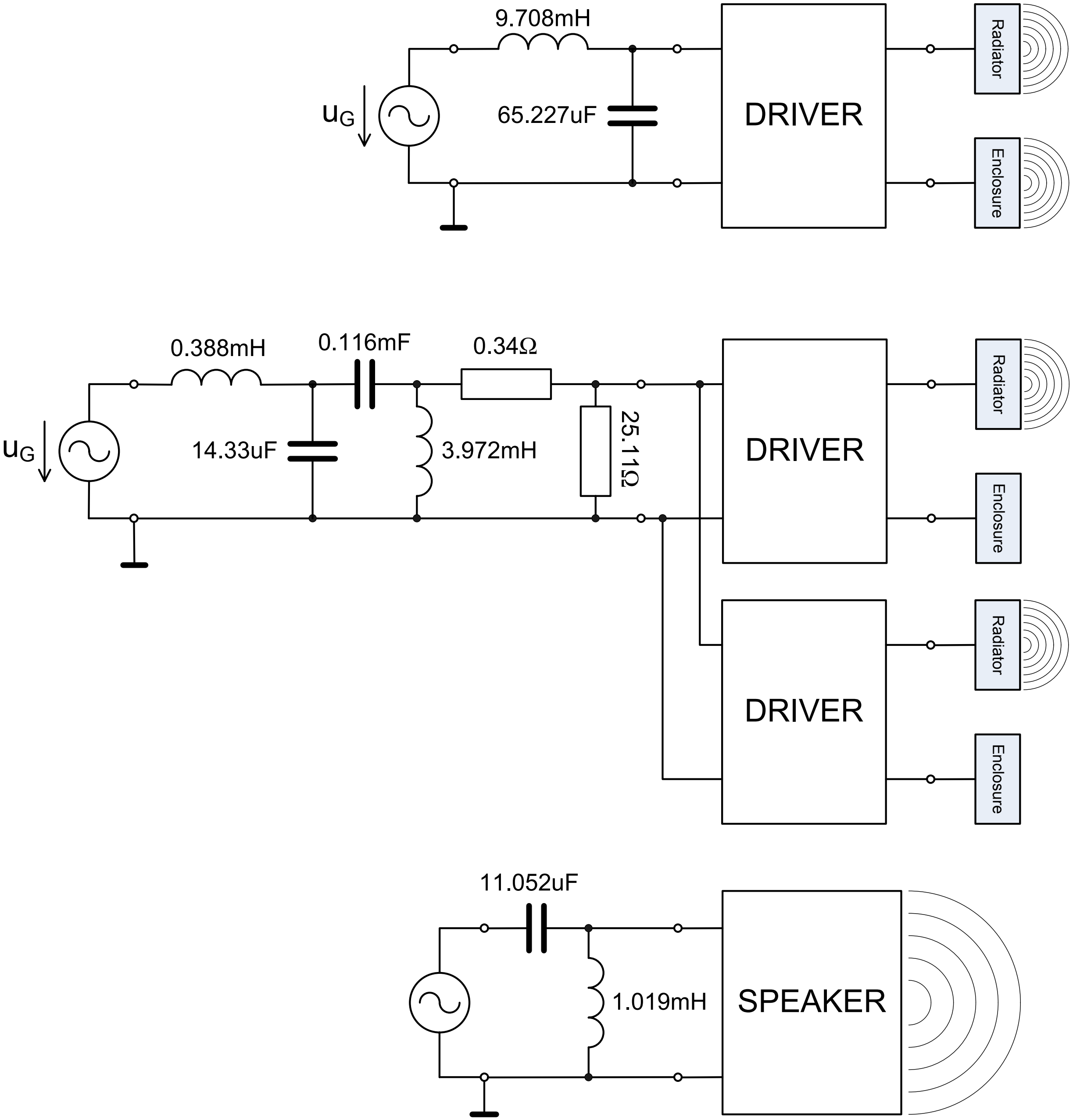
ideálny filter v tvare prenosovej funkcie

```
Def_Driver  'Woofer'
  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

Def_Driver  'Midrange'
  SD=55cm2  dD1=3.6cm  tD1=1.75cm   |Cone
  fs=68Hz  Vas=5L  Qms=2.42
  Qes=0.74  Re=6.2ohm  Le=0.31mH  ExpoLe=0.618

Def_Speaker  'Tweeter'
  Meas_Dipole
  SD=7.5cm2  tD1=5.5mm t1=3.5mm  |Convex Dome
  fs=550Hz  Vas=17.8cm3  Qms=2.425
  Bl=3.5Tm  Re=4.8ohm  Le=50uH  ExpoLe=0.618

System 'L'
  Coil      Node=1=2  L=9.708mH
  Capacitor  Node=2=0  C=65.227uF
  SynthesisInfo
    Passive  FirstNode=1  RL=6.1ohm  QL=0
    fo=200Hz  vo=1
    {b0=1;
     a2=1;  a1=2;  a0=1;  }
  Driver 'D1'  Def='Woofer'  Node=2=0=3=4
  Radiator  'Rad1'  Def='D1'    Node=3
    x=0  y=0  z=0  HAngle=0  VAngle=0
  Enclosure    'E1'  Node=4
    Vb=45L  Sb=350cm2
    fb=34Hz  dD=10cm  QD/fo=0.34  Visc=0
    x=0  y=0  z=0  HAngle=0  VAngle=0
```

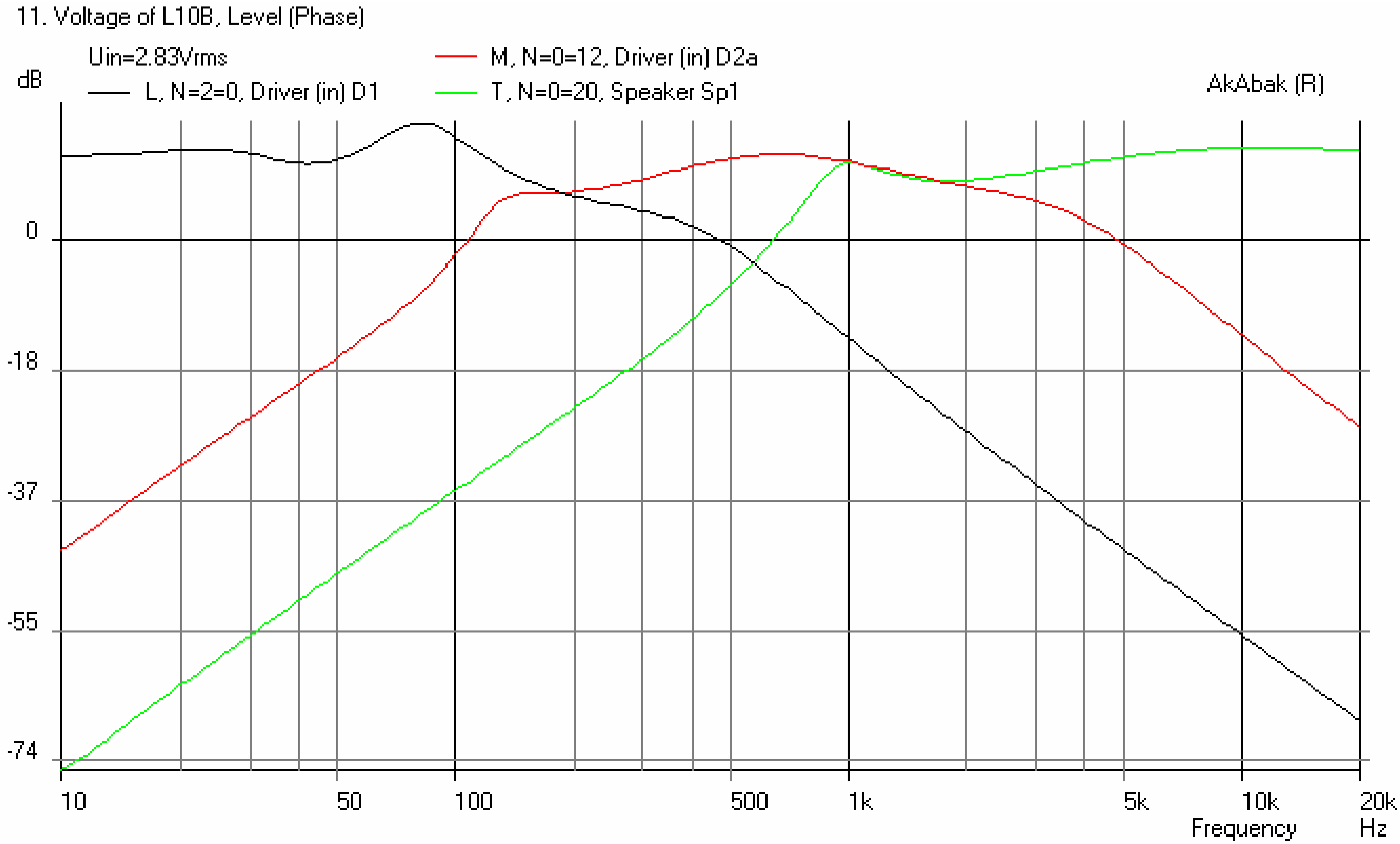
• • •

```
System 'M'
  Coil      Node=1=10  L=0.388mH
  Capacitor  Node=10=0  C=14.33uF
  Capacitor  Node=10=11  C=0.116mF
  Coil      Node=11=0  L=3.972mH
  Resistor  Node=11=12  R=0.34ohm
  Resistor  Node=12=0  R=25.11ohm
  SynthesisInfo
    Passive  FirstNode=1  RL=3.1ohm  QL=0
    fo=707.11Hz  vo=1
    {b2=1;
     a4=0.123457;  a3=0.702728;  a2=1.246914;
     a1=0.702728;  a0=0.123457;  }
  Driver 'D2a'  Def='Midrange'  Node=0=12=15=16
  Radiator  'Rad1'  Def='D2a'    Node=15
    x=0  y=0  z=0  HAngle=0  VAngle=0
  Enclosure    'E2'  Node=16
    Vb=3.2L  Sb=55cm2
  Driver 'D2b'  Def='Midrange'  Node=0=12=17=18
  Radiator  'Rad1'  Def='D2b'    Node=17
    x=0  y=10cm  z=0  HAngle=0  VAngle=0
  Enclosure    'E2'  Node=18
    Vb=3.2L  Sb=55cm2

System 'T'
  Capacitor  Node=1=20  C=11.052uF
  Coil      Node=20=0  L=1.019mH
  SynthesisInfo
    Passive  FirstNode=1  RL=4.8ohm  QL=0
    fo=1.5kHz  vo=1
    {b2=1;
     a2=1;  a1=2;  a0=1;  }
  Speaker    'Sp1'  Def='Tweeter'  Node=20=0
    x=0  y=0  z=0  HAngle=0  VAngle=0
```

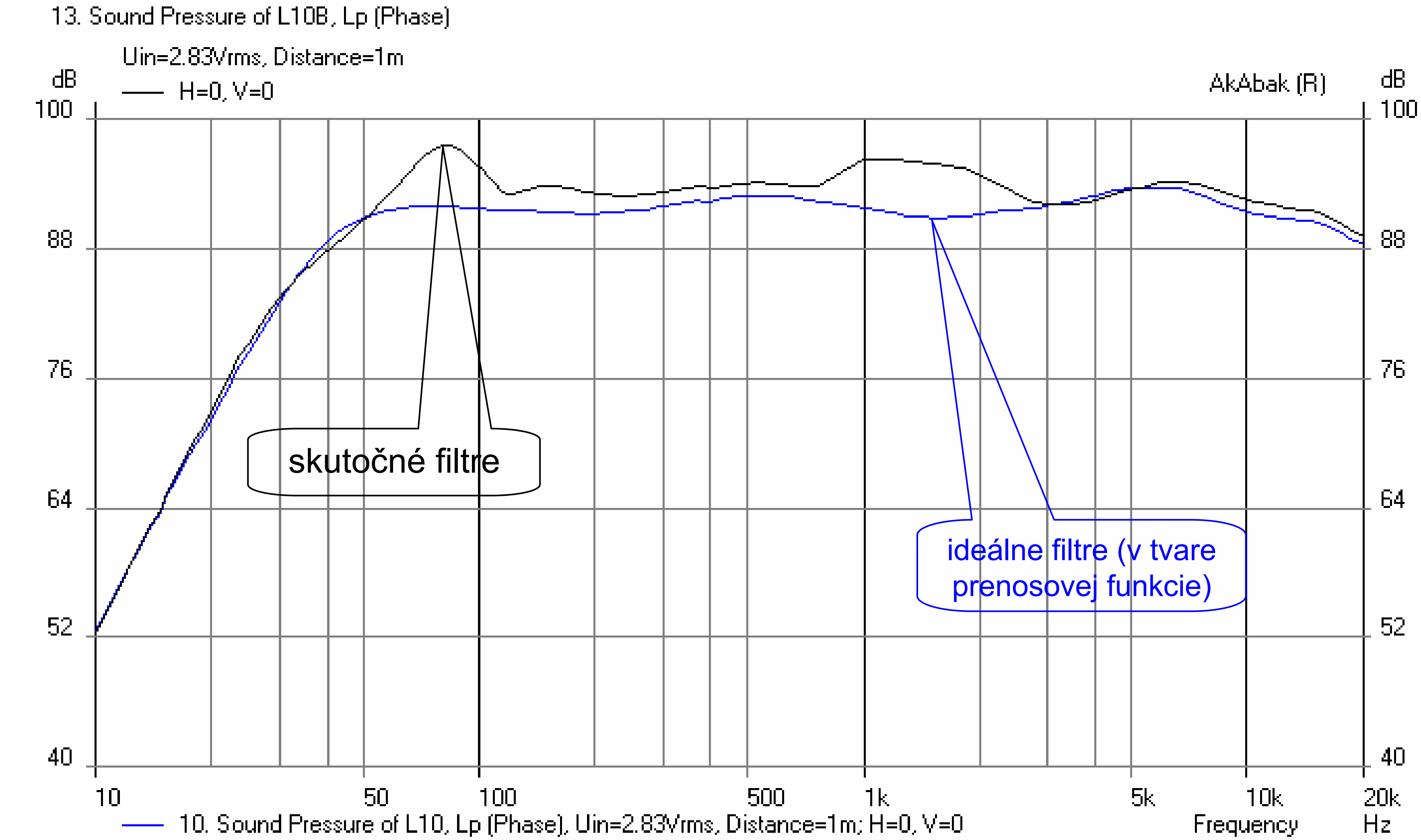
Celá sústava



Napätia na výstupe elektrických filtrov



Hladina akustického tlaku sústavy

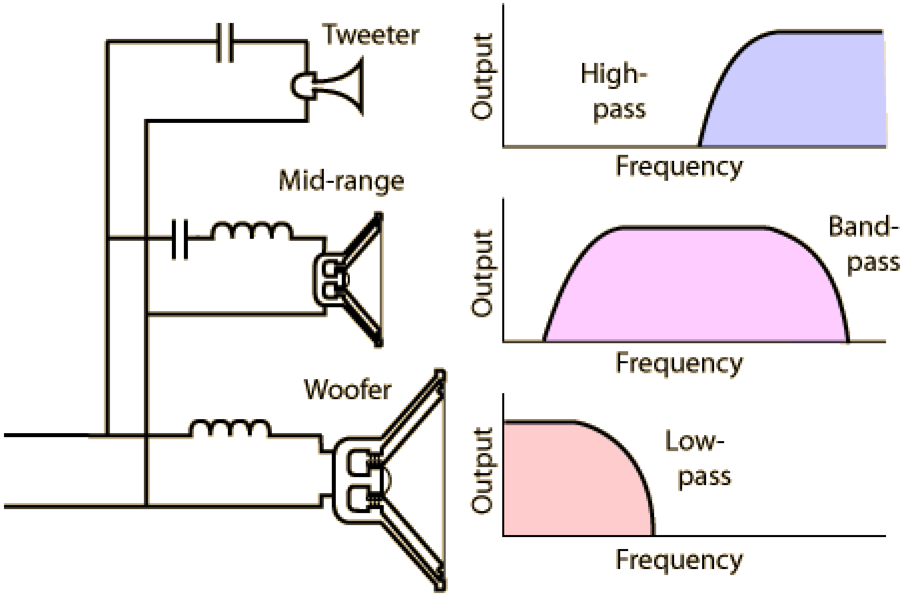


skutočné filtre

ideálne filtre (v tvare prenosovej funkcie)

Úloha výhybky

- Elektronické výhybky sú elektrické filtre, ktoré delia vstupný audiosignál do frekvenčných pásiem, vhodných na reprodukciu jednotlivými reproduktormi sústavy:
  - Dvojpásmová sústava – dolnopriepustný filter (DP) a hornopriepustný filter (HP)
  - Trojpásmová sústava – DP, pásmový filter (PP), HP
- Elektrické zapojenie
  - Sériové – filter a reproduktor v rámci pásma
  - Paralelné – pásma voči sebe



Deliaca frekvencia

- Je to frekvencia, ktorá vymedzuje hranicu medzi frekvenčnými pásmami dvoch "susedných" reproduktorov
- Pri deliacej frekvencii by mali obidva reproduktory emitovať rovnaký "osový" akustický tlak
- Typické hodnoty:
  - Dvojpásmová sústava v rozmedzí 1.5-2 kHz
  - Trojpásmová sústava v rozmedzí 300-800 Hz resp. 3-5 khz
- Presnejší odhad deliacej frekvencie:
  - Mala by byť zvolená tak, aby reproduktor neemitoval akustické vlnenie pri frekvencii väčšej, ako je frekvencia, pri ktorej kR=1 (k – vlnové číslo, R – polomer plochy ústia membrány)
  - Ak chceme reproduktor používať pri frekvencii vyššej, je potrebné osobitnú pozornosť venovať výberu (resp. návrhu) vhodného reproduktora (najmä materiál membrány)

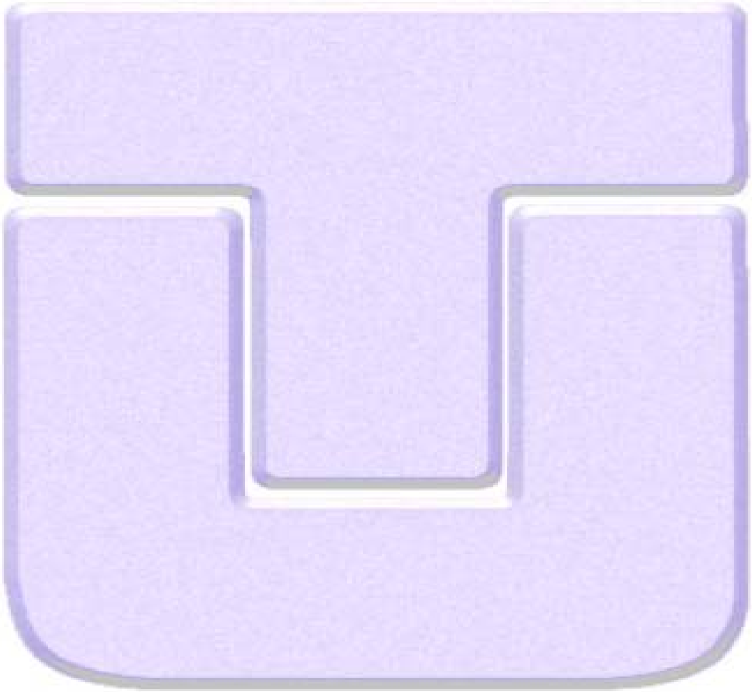
Medzná frekvencia

- Medzná frekvencia výhybkového filtra je bežne špecifikovaná ako frekvencia, pri ktorej AFCH filtra klesá o 3 dB, v špeciálnych prípadoch o 6dB:
  - DP má hornú medznú frekvenciu
  - HP má dolnú medznú frekvenciu
  - PP má dolnú aj hornú medznú frekvenciu
- Skutočná medzná frekvencia pásma sa môže odlišovať od teoreticky vypočítanej:
  - Rozdiel medzi menovitým odporom a skutočnou impedanciou reproduktora
  - Interakcia prenosových funkcii filtra a reproduktora

Rád, typ a trieda filtra

- Rád filtra – sklon AFCH v pásme zádrže
  - 1. rád – 6dB/okt. resp. 10dB/dek.
  - 2. rád – 12dB/okt. resp. 20dB/dek.
  - 3. rád - 18dB/okt. resp. 30dB/dek.
  - N-tý rád - nx6dB/okt. resp. nx10dB/dek.
- Typ filtra:
  - Dolný priepust
  - Horný priepust
  - Pásmový priepust
  - Pásmová zádrž
- Trieda filtra
  - Butterworth
  - Čebyšev
  - Bessel
  - Linkwitz-Riley
  - ...

TECHNICKÁ UNIVERZITA V KOŠICIACH



Pasívne filtre 1. rádu

$$T_w\left(s\right)=\frac{1}{1+s/\omega_w}$$

$$T_m\left(s\right)=\frac{s/\omega_{m1}}{1+s/\omega_{m1}}\frac{1}{1+s/\omega_{m2}}=\frac{s/\omega_{m1}}{1+s\left(\frac{1}{\omega_{m1}}+\frac{1}{\omega_{m2}}\right)+s^2\frac{1}{\omega_{m1}\omega_{m2}}}=\frac{s/\omega_{m1}}{1+s\left(\frac{\omega_{m1}+\omega_{m2}}{\omega_{m1}\omega_{m2}}\right)+s^2\frac{1}{\omega_{m1}\omega_{m2}}}$$

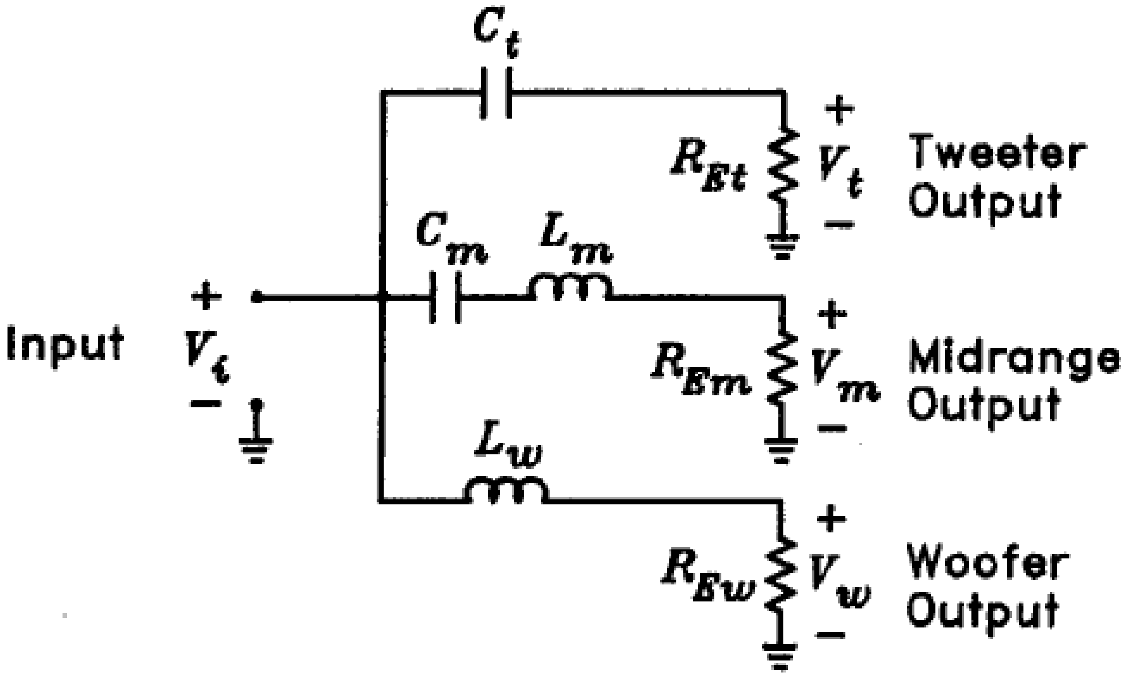
$$=\frac{s/\omega_{m1}}{1+s\left(\frac{\omega_{m1}+\omega_{m2}}{\omega_{m1}\omega_{m2}}\right)+s^2\frac{1}{\omega_{m1}\omega_{m2}}}=\frac{\sqrt{\omega_{m1}\omega_{m2}}}{\omega_{m1}+\omega_{m2}}\frac{\sqrt{\omega_{m2}}}{\sqrt{\omega_{m1}}}\frac{s\frac{1}{\sqrt{\omega_{m1}\omega_{m2}}}}{\frac{\omega_{m1}+\omega_{m2}}{\sqrt{\omega_{m1}\omega_{m2}}}+s\frac{1}{\sqrt{\omega_{m1}\omega_{m2}}}+s^2\frac{1}{\omega_{m1}\omega_{m2}}\frac{\omega_{m1}+\omega_{m2}}{\sqrt{\omega_{m1}\omega_{m2}}}}$$

$$=\frac{\sqrt{\omega_{m1}\omega_{m2}}}{\omega_{m1}+\omega_{m2}}\frac{\sqrt{\omega_{m2}}}{\sqrt{\omega_{m1}}}\frac{s\frac{1}{\sqrt{\omega_{m1}\omega_{m2}}}}{\frac{\sqrt{\omega_{m1}\omega_{m2}}}{\omega_{m1}+\omega_{m2}}+s\frac{1}{\sqrt{\omega_{m1}\omega_{m2}}}+s^2\frac{1}{\omega_{m1}\omega_{m2}}\frac{\sqrt{\omega_{m1}\omega_{m2}}}{\omega_{m1}+\omega_{m2}}}$$

$$T_t\left(s\right)=\frac{s/\omega_t}{1+s/\omega_t}$$

$\omega_w,\omega_{m1},\omega_{m2},\omega_{wt}$ − medzné frekvencie (-3dB)

Pasívna výhybka 1. rádu



$$L_w = \frac{R_{Ew}}{2\pi f_w}$$

$$C_m = \frac{1}{2\pi f_{m1} R_{Em}}$$

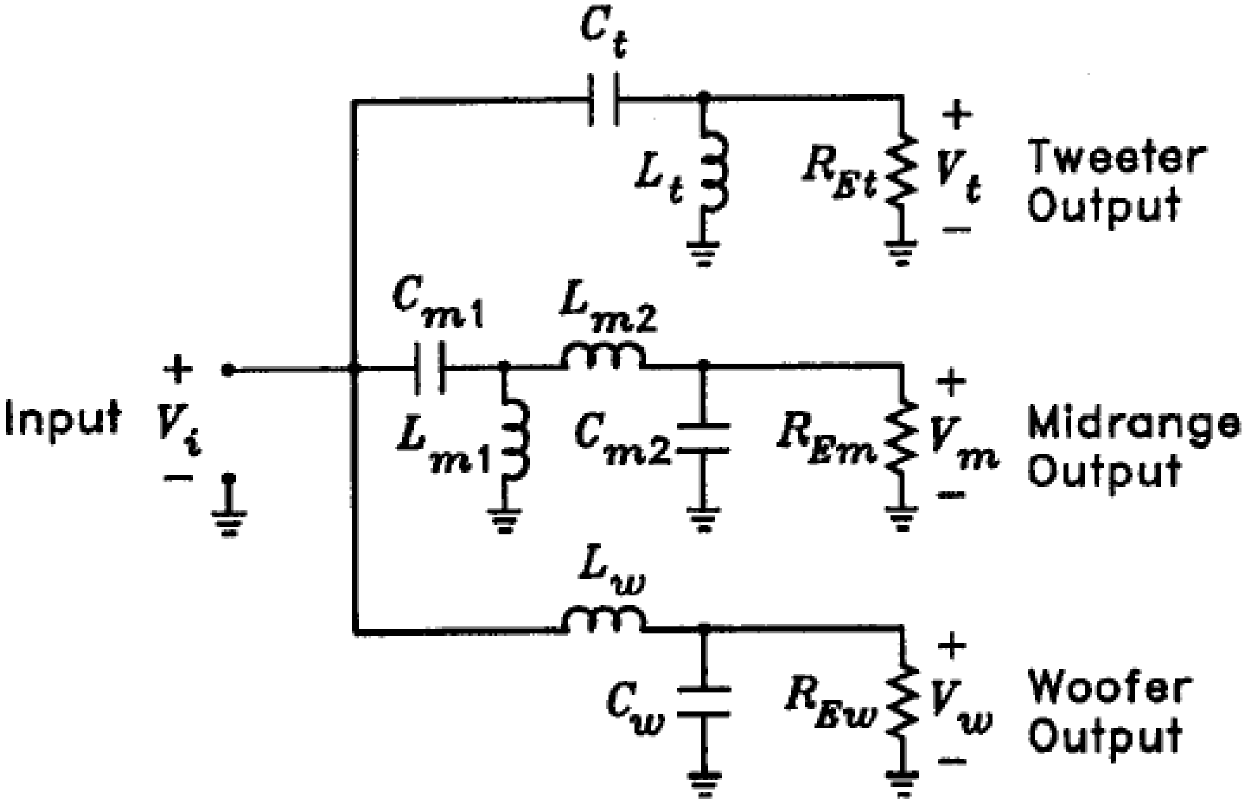
$$L_m = \frac{R_{Em}}{2\pi f_{m2}}$$

$$C_m = \frac{1}{2\pi f_t R_{Et}}$$

$$T_w(s) = \frac{1}{1 + s/\omega_w} \quad T_m(s) = \frac{s/\omega_{m1}}{1 + s/\omega_{m1}} \frac{1}{1 + s/\omega_{m2}} \quad T_t(s) = \frac{s/\omega_t}{1 + s/\omega_t}$$

$\omega_w, \omega_{m1}, \omega_{m2}, \omega_{wt}$ – medzné frekvencie (-3dB)

Pasívna výhybka 2. rádu



$$T_w(s) = \frac{1}{(s/\omega_w)^2 + (1/Q_w)(s/\omega_w) + 1} \tag{9.3}$$

$$T_m(s) = \frac{(s/\omega_{m1})^2}{(s/\omega_{m1})^2 + (1/Q_{m1})(s/\omega_{m1}) + 1} \times \frac{1}{(s/\omega_{m2})^2 + (1/Q_{m2})(s/\omega_{m2}) + 1} \tag{9.4}$$

$$T_t(s) = \frac{(s/\omega_t)^2}{(s/\omega_t)^2 + (1/Q_t)(s/\omega_t) + 1} \tag{9.5}$$

$$L_w = \frac{R_{Ew}}{2\pi f_w Q_w} \qquad C_w = \frac{Q_w}{2\pi f_w R_{Ew}} \qquad L_{m1} = \frac{R_{Em}}{2\pi f_{m1} Q_{m1}} \qquad C_{m1} = \frac{Q_{m1}}{2\pi f_{m1} R_{Em}} \tag{9.6}$$

$$L_{m2} = \frac{R_{Em}}{2\pi f_{m2} Q_{m2}} \qquad C_{m2} = \frac{Q_{m2}}{2\pi f_{m2} R_{Em}} \qquad L_t = \frac{R_{Et}}{2\pi f_t Q_t} \qquad C_t = \frac{Q_t}{2\pi f_t R_{Et}} \tag{9.7}$$

Pasívna výhybka 3. rádu

- …

$$C_1 = \frac{1}{3\pi f_c R_E} \qquad C_2 = 3C_1 \qquad L = \frac{3R_E}{8\pi f_c}$$

$$L_2 = \frac{R_E}{4\pi f_c} \qquad L_1 = 3L_2 \qquad C = \frac{2}{3\pi f_c R_E}$$

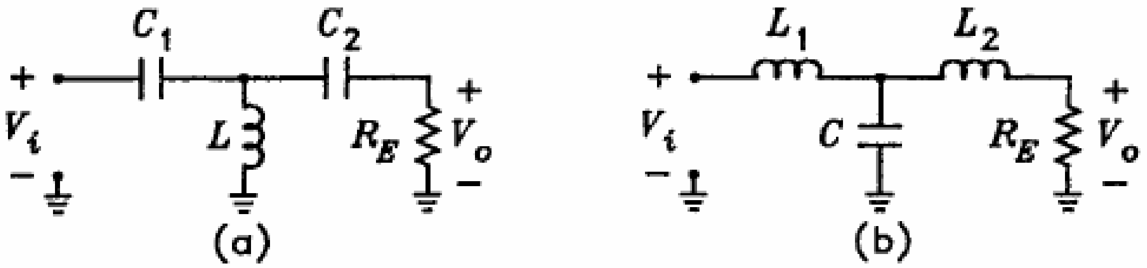


Figure 9.4: Third-order (a) high-pass and (b) low-pass filters.

Návrh odporového deliča na vyrovnanie citlivosti reproduktorov

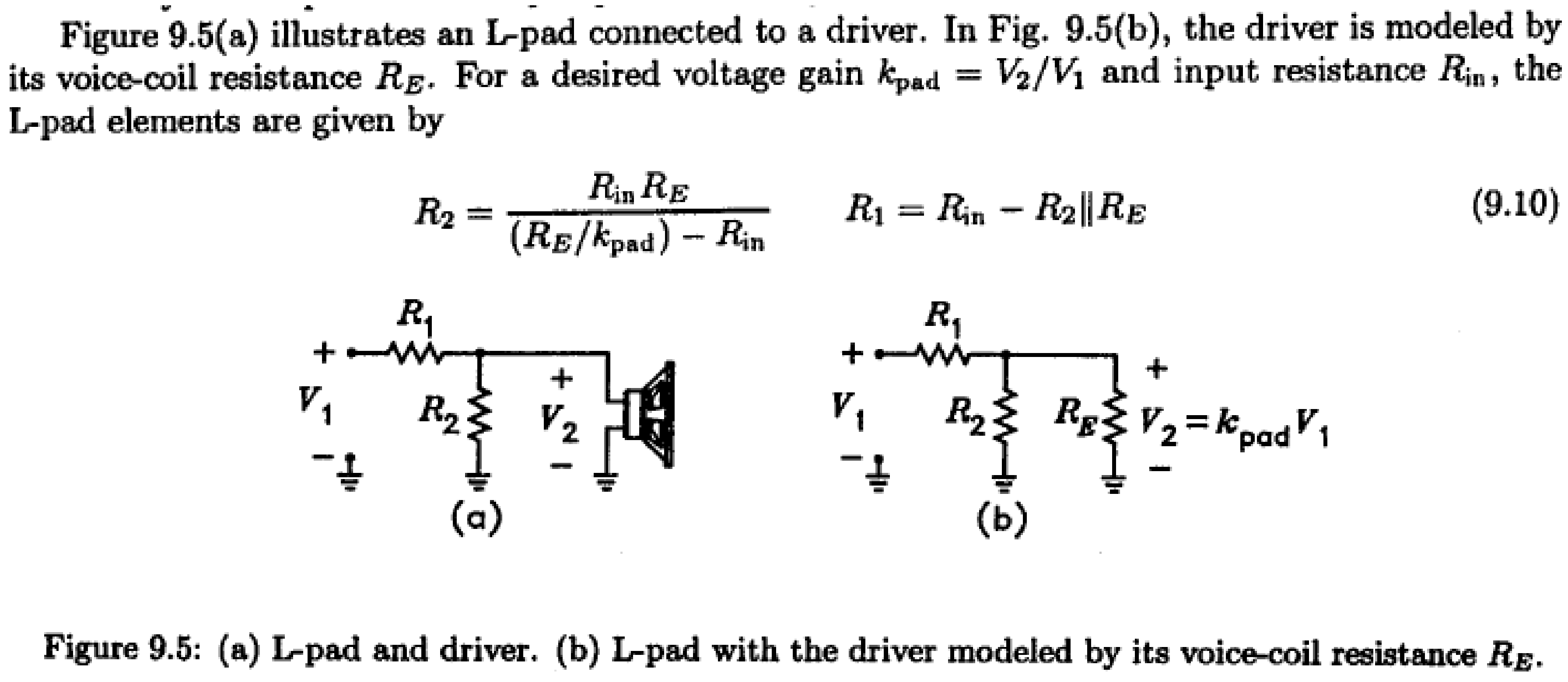


Figure 9.5(a) illustrates an L-pad connected to a driver. In Fig. 9.5(b), the driver is modeled by its voice-coil resistance R_E. For a desired voltage gain $k_{\text{pad}} = V_2/V_1$ and input resistance R_{in}, the L-pad elements are given by

$$R_2 = \frac{R_{\text{in}} R_E}{(R_E/k_{\text{pad}}) - R_{\text{in}}} \qquad R_1 = R_{\text{in}} - R_2 \| R_E \tag{9.10}$$

Figure 9.5: (a) L-pad and driver. (b) L-pad with the driver modeled by its voice-coil resistance R_E.

$$k_{\text{pad}} = \frac{p^{1V}_{\text{sens1}}}{p^{1V}_{\text{sens2}}} = \sqrt{\frac{R_{E2}}{R_{E1}} \times \frac{\eta_{01}}{\eta_{02}}} \qquad k_{\text{pad}} = 10^{(SPL^{1V}_{\text{sens1}} - SPL^{1V}_{\text{sens2}})/20} = \sqrt{\frac{R_{E2}}{R_{E1}}}\, 10^{(SPL^{1W}_{\text{sens1}} - SPL^{1W}_{\text{sens2}})/20}$$

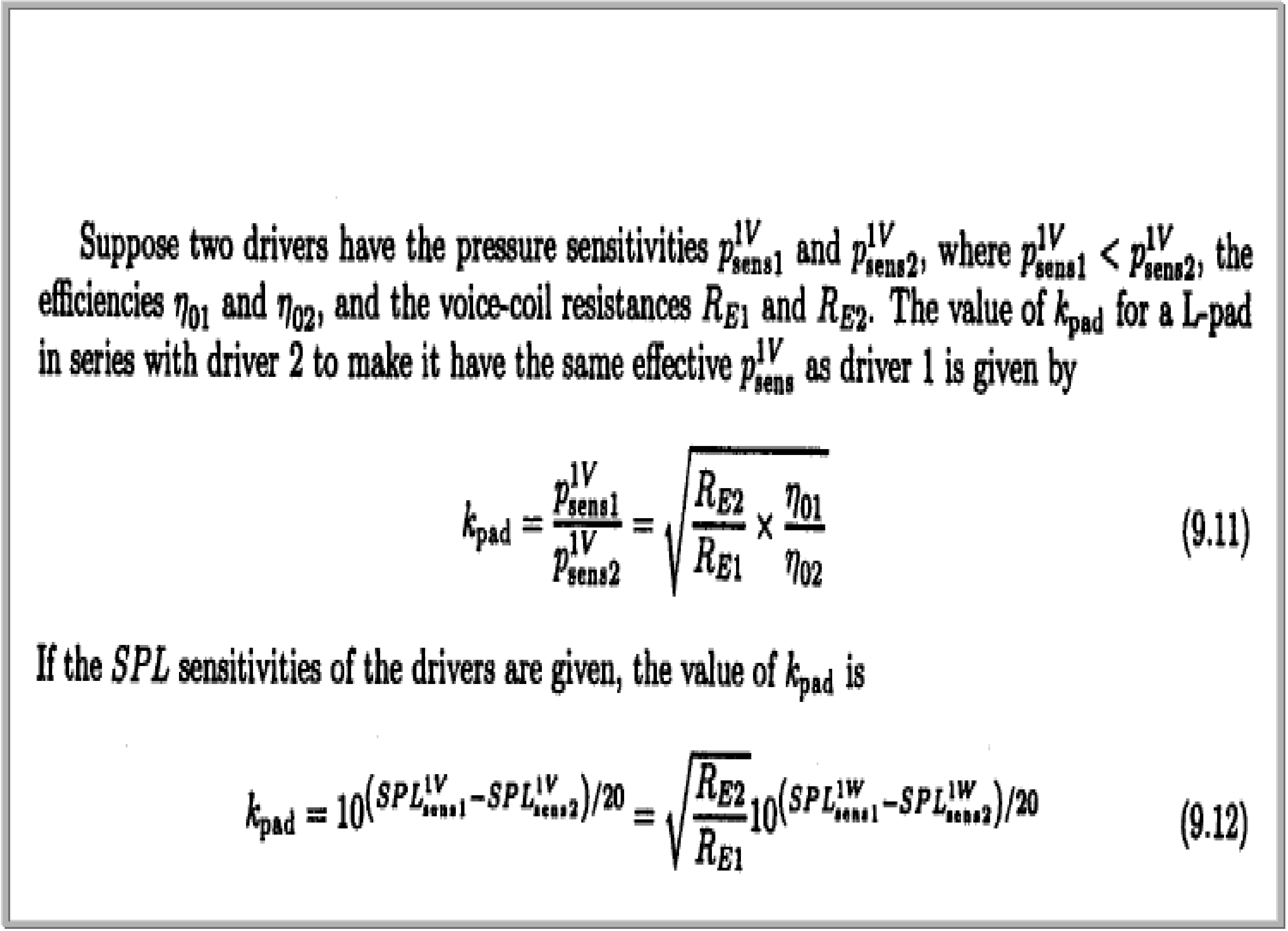
Návrh odporového deliča na vyrovnanie citlivosti reproduktorov

- odporový delič slúži na vyrovnanie citlivosti reproduktorov
- zapája sa na vstup reproduktora s vyššou citlivosťou – cieľom je znížiť napätie na jeho vstupe

$$R_1 = R_{in} - \frac{R_2 R_{EVC}}{R_2 + R_{EVC}}$$

$$R_2 = \frac{R_{in} R_{EVC} k_{pad}}{R_{EVC} - R_{in} k_{pad}}$$

$-$



Suppose two drivers have the pressure sensitivities $p^{1V}_{\text{sens}1}$ and $p^{1V}_{\text{sens}2}$, where $p^{1V}_{\text{sens}1} < p^{1V}_{\text{sens}2}$, the efficiencies η_{01} and η_{02}, and the voice-coil resistances R_{E1} and R_{E2}. The value of k_{pad} for a L-pad in series with driver 2 to make it have the same effective p^{1V}_{sens} as driver 1 is given by

$$k_{\text{pad}} = \frac{p^{1V}_{\text{sens}1}}{p^{1V}_{\text{sens}2}} = \sqrt{\frac{R_{E2}}{R_{E1}} \times \frac{\eta_{01}}{\eta_{02}}} \tag{9.11}$$

If the SPL sensitivities of the drivers are given, the value of k_{pad} is

$$k_{\text{pad}} = 10^{\left(SPL^{1V}_{\text{sens}1} - SPL^{1V}_{\text{sens}2}\right)/20} = \sqrt{\frac{R_{E2}}{R_{E1}}}\,10^{\left(SPL^{1W}_{\text{sens}1} - SPL^{1W}_{\text{sens}2}\right)/20} \tag{9.12}$$

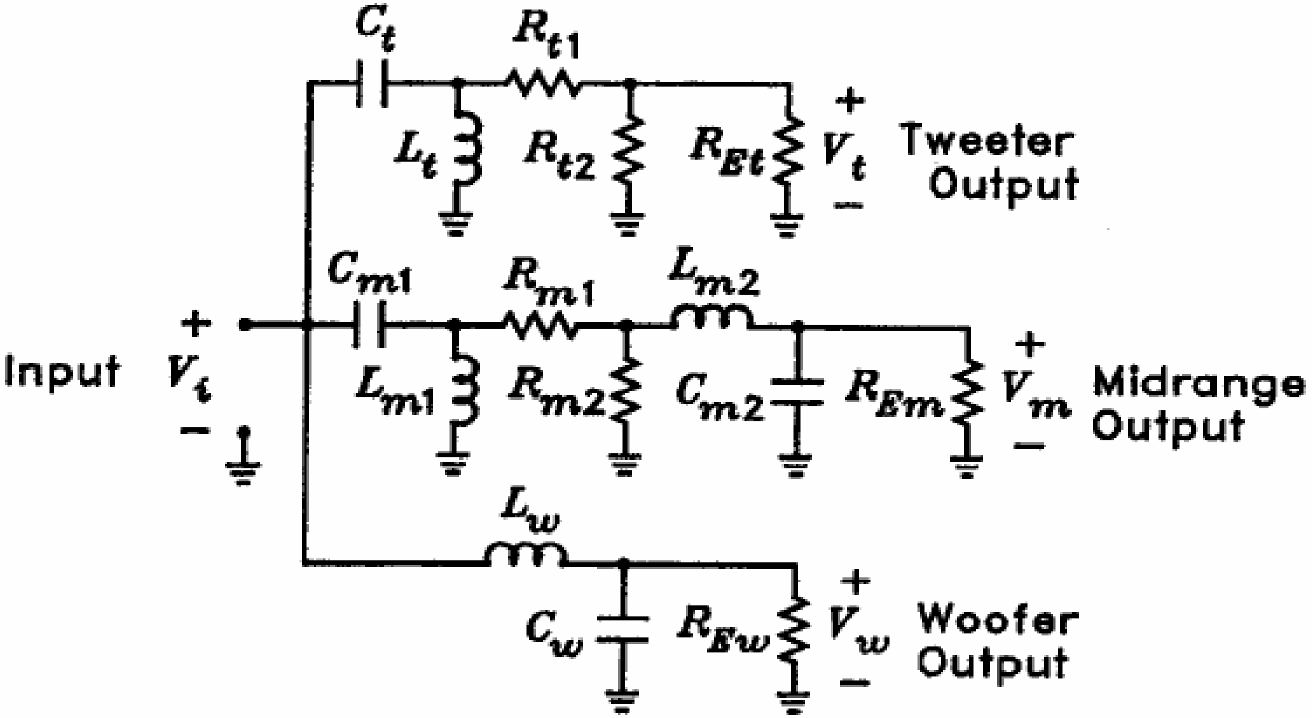


Figure 9.6: Example crossover network with two L-pads.

Kompenzácia vstupnej impedancie

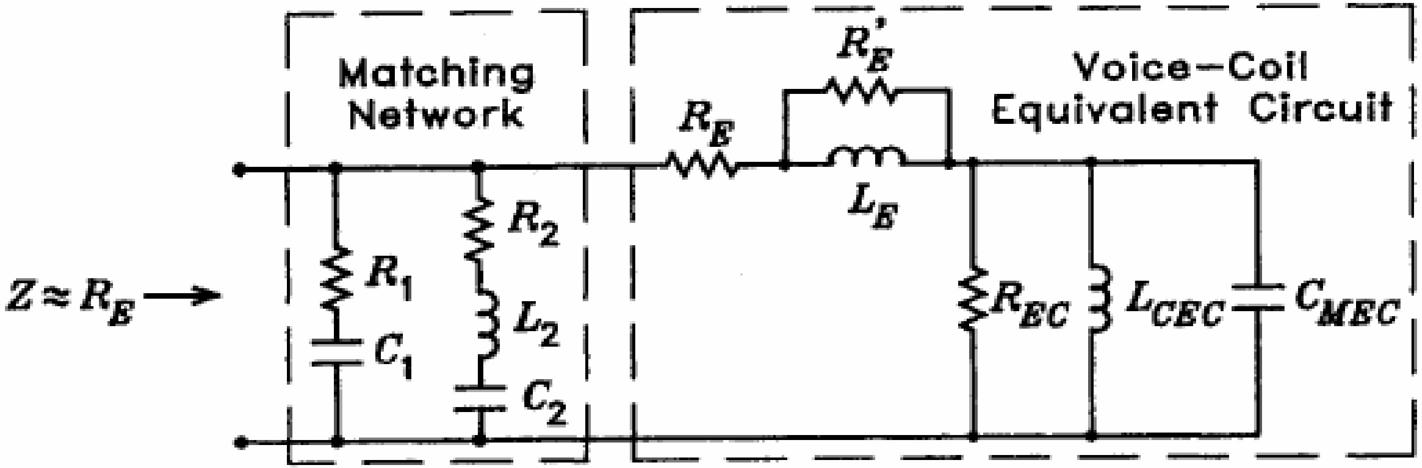
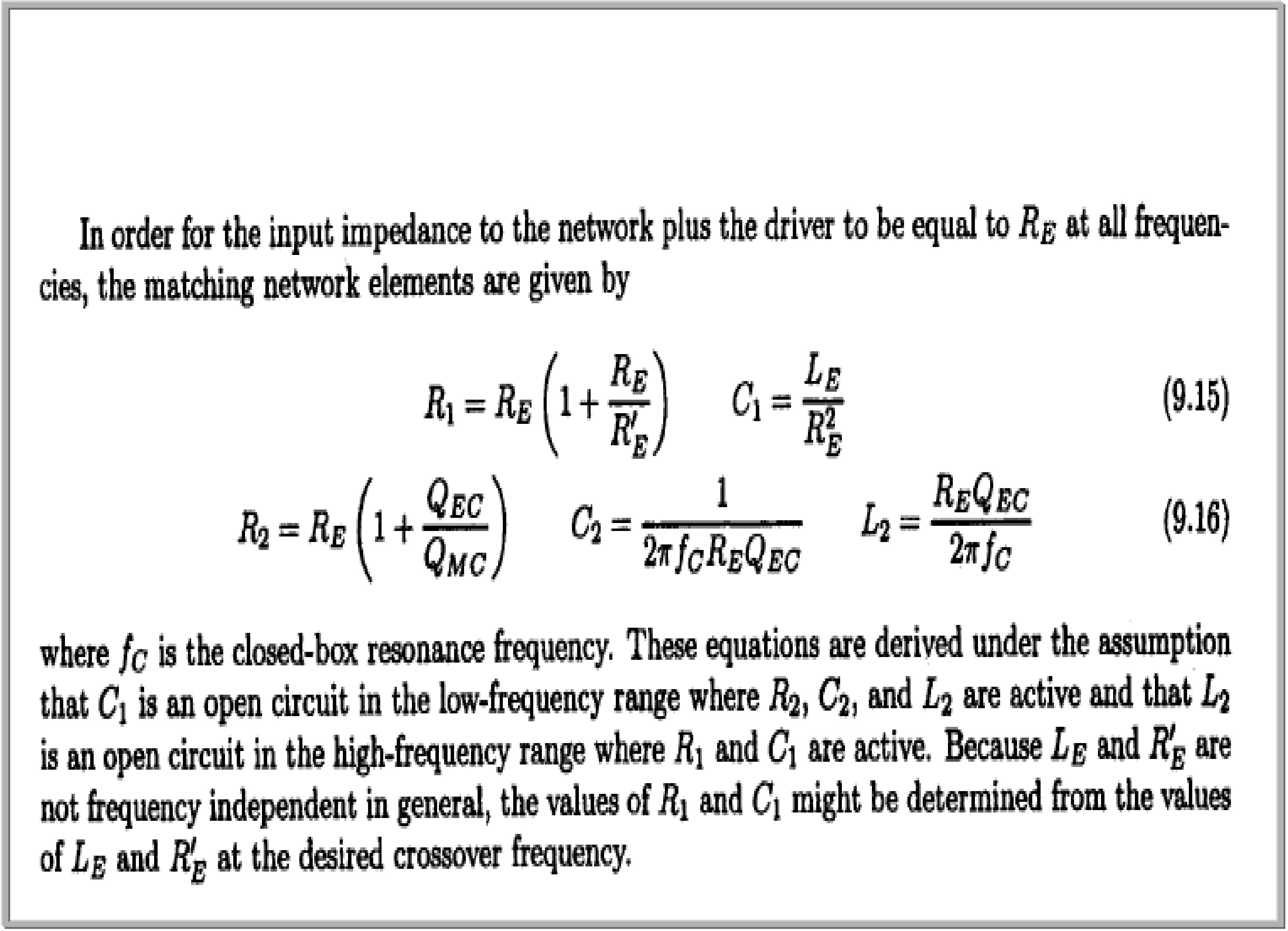


Figure 9.7: Voice-coil equivalent circuit with matching networks.

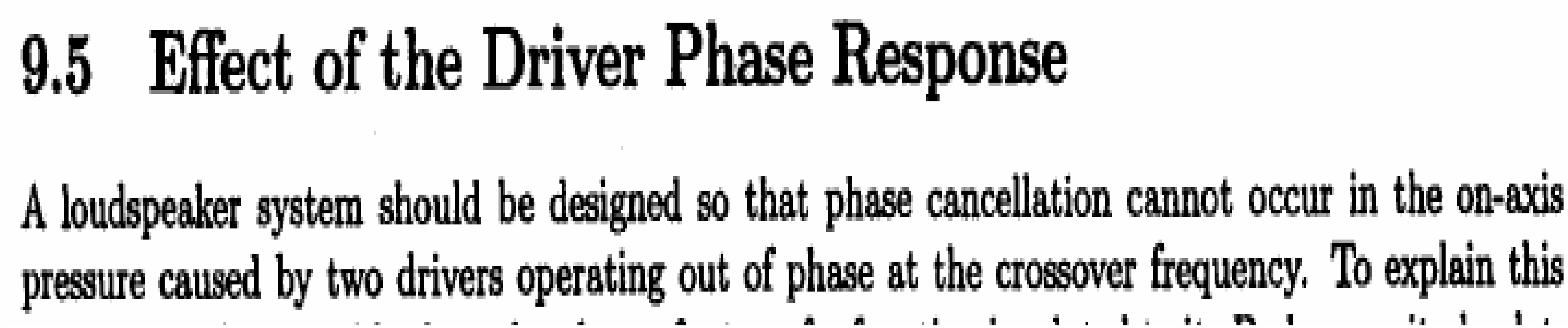


In order for the input impedance to the network plus the driver to be equal to R_E at all frequencies, the matching network elements are given by

$$R_1 = R_E\left(1+\frac{R_E}{R'_E}\right) \qquad C_1 = \frac{L_E}{R_E^2} \tag{9.15}$$

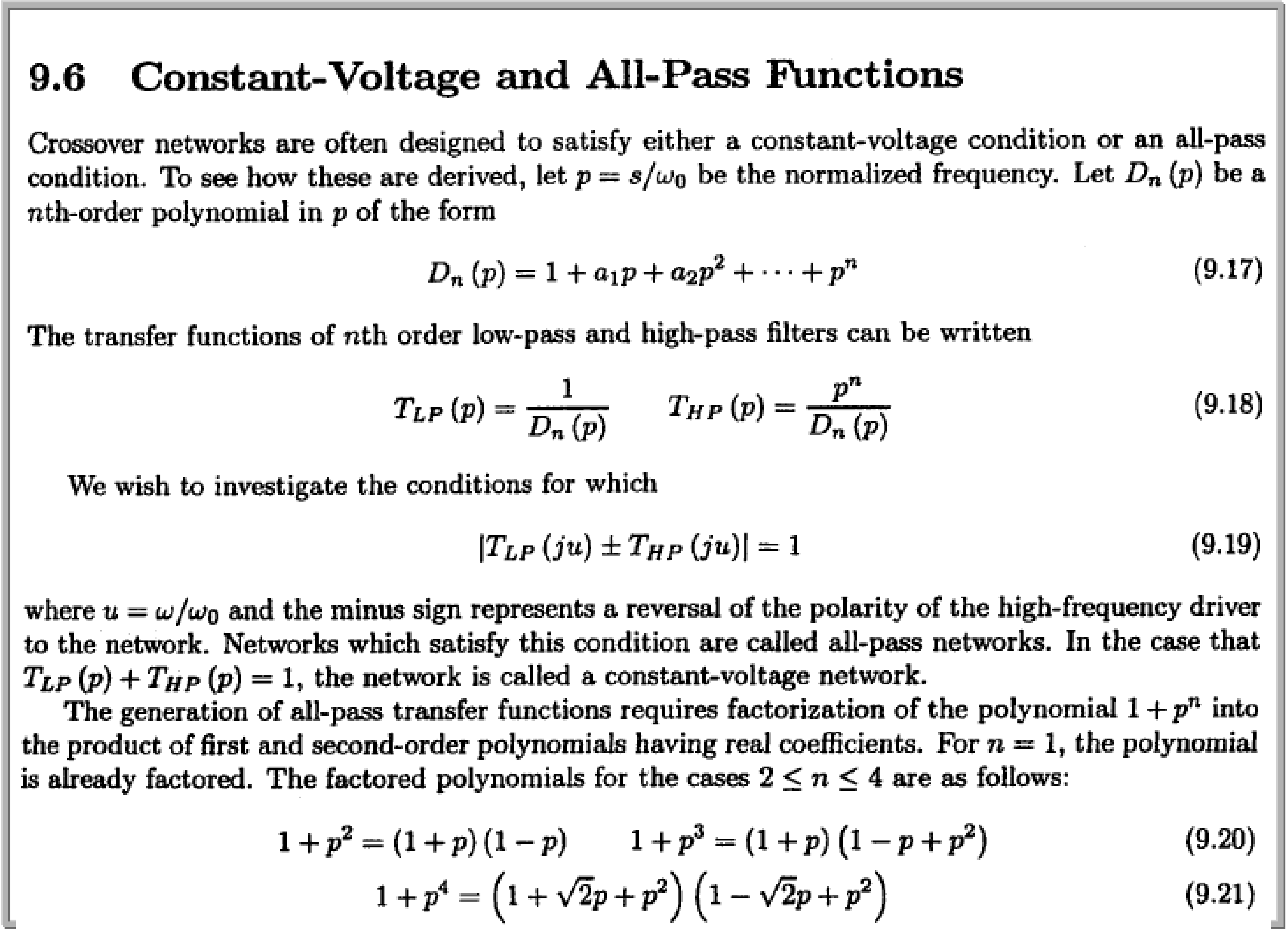
$$R_2 = R_E\left(1+\frac{Q_{EC}}{Q_{MC}}\right) \qquad C_2 = \frac{1}{2\pi f_C R_E Q_{EC}} \qquad L_2 = \frac{R_E Q_{EC}}{2\pi f_C} \tag{9.16}$$

where f_C is the closed-box resonance frequency. These equations are derived under the assumption that C_1 is an open circuit in the low-frequency range where R_2, C_2, and L_2 are active and that L_2 is an open circuit in the high-frequency range where R_1 and C_1 are active. Because L_E and R'_E are not frequency independent in general, the values of R_1 and C_1 might be determined from the values of L_E and R'_E at the desired crossover frequency.



9.5 Effect of the Driver Phase Response

A loudspeaker system should be designed so that phase cancellation cannot occur in the on-axis pressure caused by two drivers operating out of phase at the crossover frequency. To explain this



9.6 Constant-Voltage and All-Pass Functions

Crossover networks are often designed to satisfy either a constant-voltage condition or an all-pass condition. To see how these are derived, let $p = s/\omega_0$ be the normalized frequency. Let $D_n(p)$ be a nth-order polynomial in p of the form

$$D_n(p) = 1 + a_1 p + a_2 p^2 + \cdots + p^n \tag{9.17}$$

The transfer functions of nth order low-pass and high-pass filters can be written

$$T_{LP}(p) = \frac{1}{D_n(p)} \qquad T_{HP}(p) = \frac{p^n}{D_n(p)} \tag{9.18}$$

We wish to investigate the conditions for which

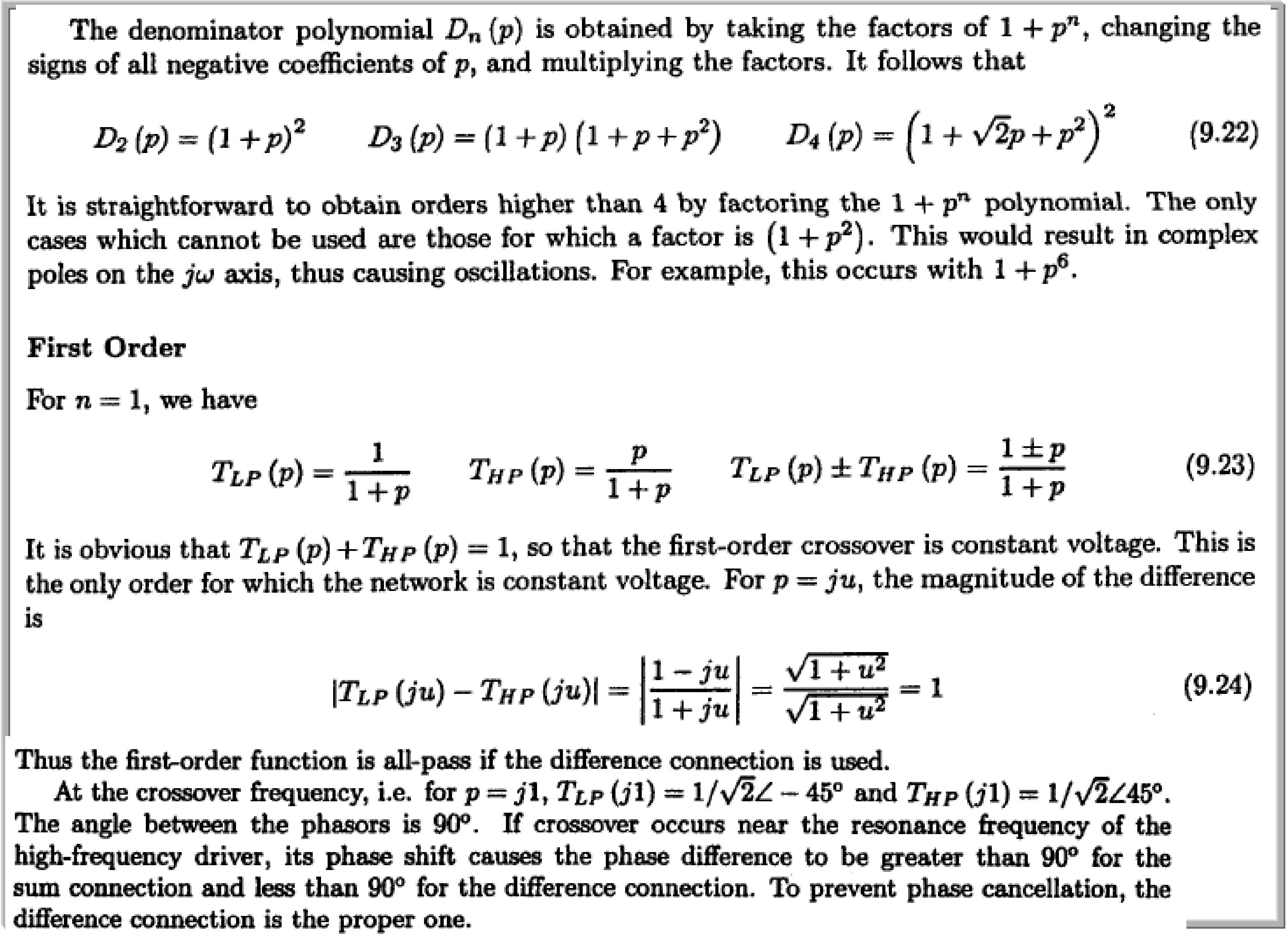
$$|T_{LP}(ju) \pm T_{HP}(ju)| = 1 \tag{9.19}$$

where $u = \omega/\omega_0$ and the minus sign represents a reversal of the polarity of the high-frequency driver to the network. Networks which satisfy this condition are called all-pass networks. In the case that $T_{LP}(p) + T_{HP}(p) = 1$, the network is called a constant-voltage network.

The generation of all-pass transfer functions requires factorization of the polynomial $1 + p^n$ into the product of first and second-order polynomials having real coefficients. For $n = 1$, the polynomial is already factored. The factored polynomials for the cases $2 \leq n \leq 4$ are as follows:

$$1 + p^2 = (1 + p)(1 - p) \qquad 1 + p^3 = (1 + p)\left(1 - p + p^2\right) \tag{9.20}$$

$$1 + p^4 = \left(1 + \sqrt{2}p + p^2\right)\left(1 - \sqrt{2}p + p^2\right) \tag{9.21}$$



The denominator polynomial $D_n(p)$ is obtained by taking the factors of $1+p^n$, changing the signs of all negative coefficients of p, and multiplying the factors. It follows that

$$D_2(p) = (1+p)^2 \qquad D_3(p) = (1+p)\left(1+p+p^2\right) \qquad D_4(p) = \left(1+\sqrt{2}p+p^2\right)^2 \tag{9.22}$$

It is straightforward to obtain orders higher than 4 by factoring the $1+p^n$ polynomial. The only cases which cannot be used are those for which a factor is $\left(1+p^2\right)$. This would result in complex poles on the $j\omega$ axis, thus causing oscillations. For example, this occurs with $1+p^6$.

First Order

For $n=1$, we have

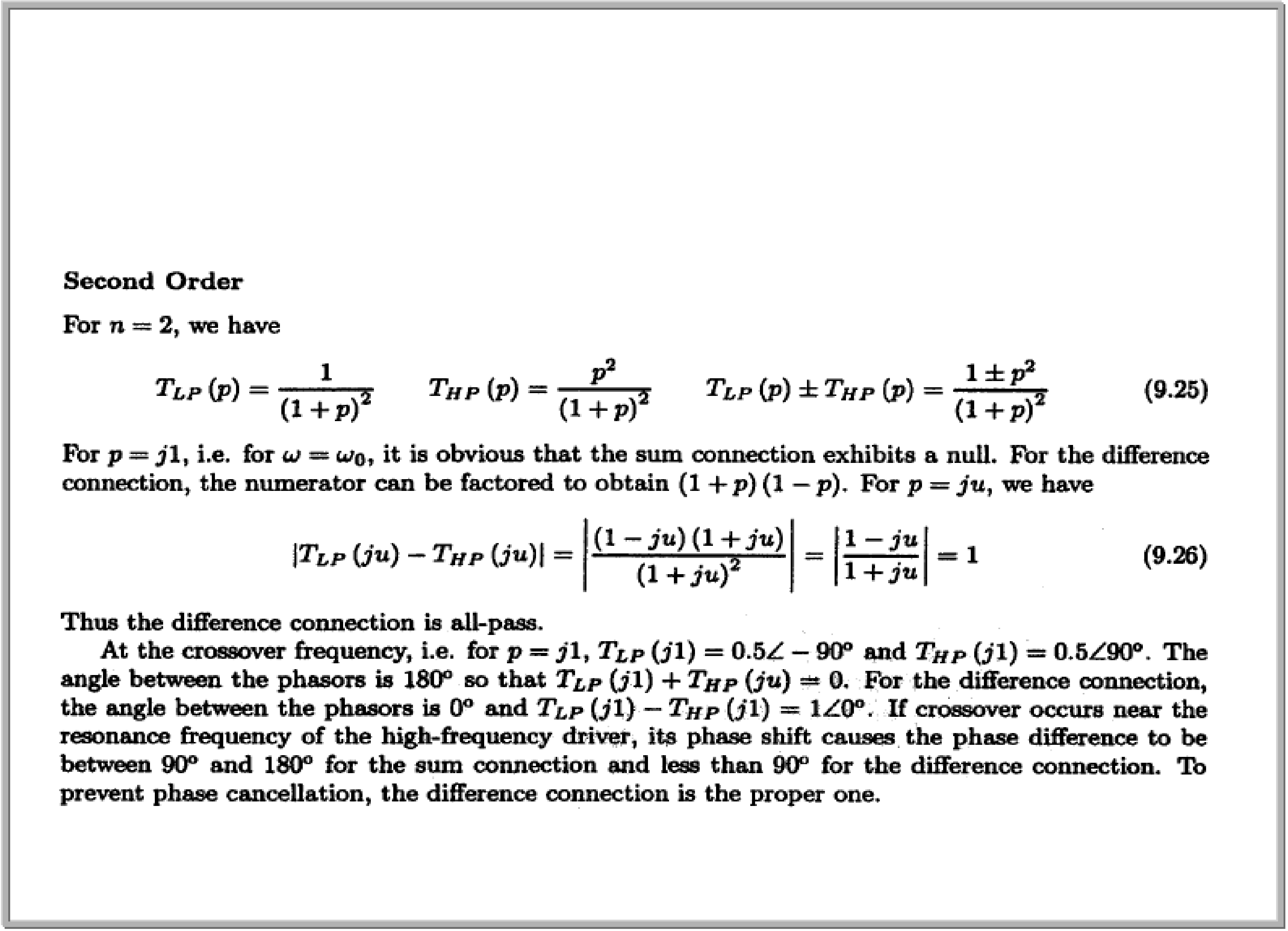
$$T_{LP}(p) = \frac{1}{1+p} \qquad T_{HP}(p) = \frac{p}{1+p} \qquad T_{LP}(p) \pm T_{HP}(p) = \frac{1 \pm p}{1+p} \tag{9.23}$$

It is obvious that $T_{LP}(p) + T_{HP}(p) = 1$, so that the first-order crossover is constant voltage. This is the only order for which the network is constant voltage. For $p = ju$, the magnitude of the difference is

$$\left|T_{LP}(ju) - T_{HP}(ju)\right| = \left|\frac{1-ju}{1+ju}\right| = \frac{\sqrt{1+u^2}}{\sqrt{1+u^2}} = 1 \tag{9.24}$$

Thus the first-order function is all-pass if the difference connection is used.

At the crossover frequency, i.e. for $p = j1$, $T_{LP}(j1) = 1/\sqrt{2}\angle -45^\circ$ and $T_{HP}(j1) = 1/\sqrt{2}\angle 45^\circ$. The angle between the phasors is 90°. If crossover occurs near the resonance frequency of the high-frequency driver, its phase shift causes the phase difference to be greater than 90° for the sum connection and less than 90° for the difference connection. To prevent phase cancellation, the difference connection is the proper one.



Second Order

For $n = 2$, we have

$$T_{LP}(p) = \frac{1}{(1+p)^2} \qquad T_{HP}(p) = \frac{p^2}{(1+p)^2} \qquad T_{LP}(p) \pm T_{HP}(p) = \frac{1 \pm p^2}{(1+p)^2} \tag{9.25}$$

For $p = j1$, i.e. for $\omega = \omega_0$, it is obvious that the sum connection exhibits a null. For the difference connection, the numerator can be factored to obtain $(1+p)(1-p)$. For $p = ju$, we have

$$|T_{LP}(ju) - T_{HP}(ju)| = \left| \frac{(1-ju)(1+ju)}{(1+ju)^2} \right| = \left| \frac{1-ju}{1+ju} \right| = 1 \tag{9.26}$$

Thus the difference connection is all-pass.

At the crossover frequency, i.e. for $p = j1$, $T_{LP}(j1) = 0.5\angle -90^\circ$ and $T_{HP}(j1) = 0.5\angle 90^\circ$. The angle between the phasors is 180° so that $T_{LP}(j1) + T_{HP}(ju) \doteq 0$. For the difference connection, the angle between the phasors is 0° and $T_{LP}(j1) - T_{HP}(j1) = 1\angle 0^\circ$. If crossover occurs near the resonance frequency of the high-frequency driver, its phase shift causes the phase difference to be between 90° and 180° for the sum connection and less than 90° for the difference connection. To prevent phase cancellation, the difference connection is the proper one.

Third Order

For $n = 3$, we have

$$T_{LP}(p) = \frac{1}{(1+p)(1+p+p^2)} \qquad T_{HP}(p) = \frac{p^3}{(1+p)(1+p+p^2)} \tag{9.27}$$

The sum and difference are

$$T_{LP}(p) \pm T_{HP}(p) = \frac{1 \pm p^3}{(1+p)(1+p+p^2)} = \frac{(1 \pm p)(1 \mp p + p^2)}{(1+p)(1+p+p^2)} \tag{9.28}$$

For the sum connection, the $(1+p)$ factors cancel. For $p = ju$, the magnitude of the sum is

$$|T_{LP}(ju) + T_{HP}(ju)| = \left|\frac{1 - ju - u^2}{1 + ju - u^2}\right| = \frac{\sqrt{(1-u^2)^2 + u^2}}{\sqrt{(1-u^2)^2 + u^2}} = 1 \tag{9.29}$$

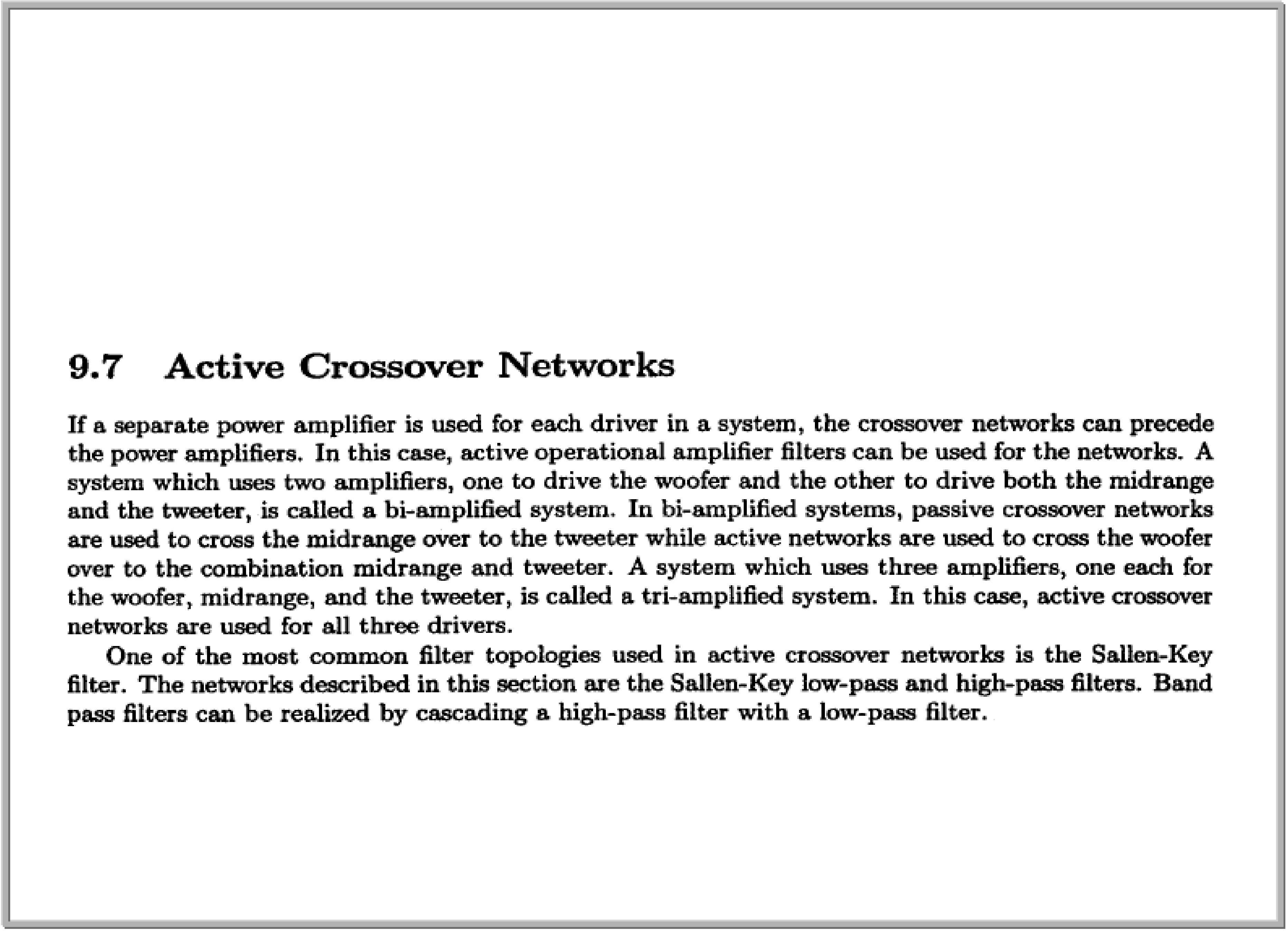
which is all-pass.

For the difference connection, the $(1+p+p^2)$ factors cancel. For $p = ju$, the magnitude of the difference is

$$|T_{LP}(ju) - T_{HP}(ju)| = \left|\frac{1 - ju}{1 + ju}\right| = \frac{\sqrt{1+u^2}}{\sqrt{1+u^2}} = 1 \tag{9.30}$$

which is also all-pass. The first-order all-pass response of the difference connection results in less phase shift than that of the second-order all-pass response of the sum connection.

At the crossover frequency, i.e. for $p = j1$, $T_{LP}(j1) = 1/\sqrt{2}\angle{-135^\circ}$ and $T_{HP}(j1) = 1/\sqrt{2}\angle 135^\circ$. The angle between the phasors is 90°. If crossover occurs near the resonance frequency of the high-frequency driver, its phase shift causes the phase difference to be less than 90° for the sum connection and greater than 90° for the difference connection. To prevent phase cancellation, the sum connection is the proper one.



9.7 Active Crossover Networks

If a separate power amplifier is used for each driver in a system, the crossover networks can precede the power amplifiers. In this case, active operational amplifier filters can be used for the networks. A system which uses two amplifiers, one to drive the woofer and the other to drive both the midrange and the tweeter, is called a bi-amplified system. In bi-amplified systems, passive crossover networks are used to cross the midrange over to the tweeter while active networks are used to cross the woofer over to the combination midrange and tweeter. A system which uses three amplifiers, one each for the woofer, midrange, and the tweeter, is called a tri-amplified system. In this case, active crossover networks are used for all three drivers.

One of the most common filter topologies used in active crossover networks is the Sallen-Key filter. The networks described in this section are the Sallen-Key low-pass and high-pass filters. Band pass filters can be realized by cascading a high-pass filter with a low-pass filter.

Second Order

Figure 9.14(a) shows the diagram of a second-order Sallen-Key low-pass filter with unity voltage gain in its passband. This filter has the transfer function

$$\frac{V_{o\ell}}{V_i} = \frac{1}{(s/\omega_1)^2 + (1/Q_1)(s/\omega_1) + 1} \qquad (9.37)$$

where ω_1 is the radian resonance frequency and Q_1 is the quality factor. Let $\omega_1 = 2\pi f_1$, Q_1, R_1 and R_2 be specified. The values of C_1 and C_2 are given by

$$C_1 = \frac{Q_1}{2\pi f_1}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad C_2 = \frac{1}{2\pi f_1 (R_1 + R_2) Q_1} \qquad (9.38)$$

The filter is often designed with $R_1 = R_2$.

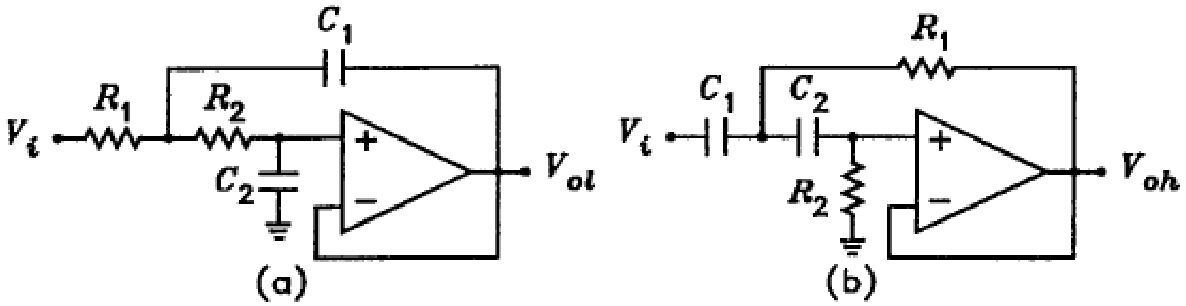
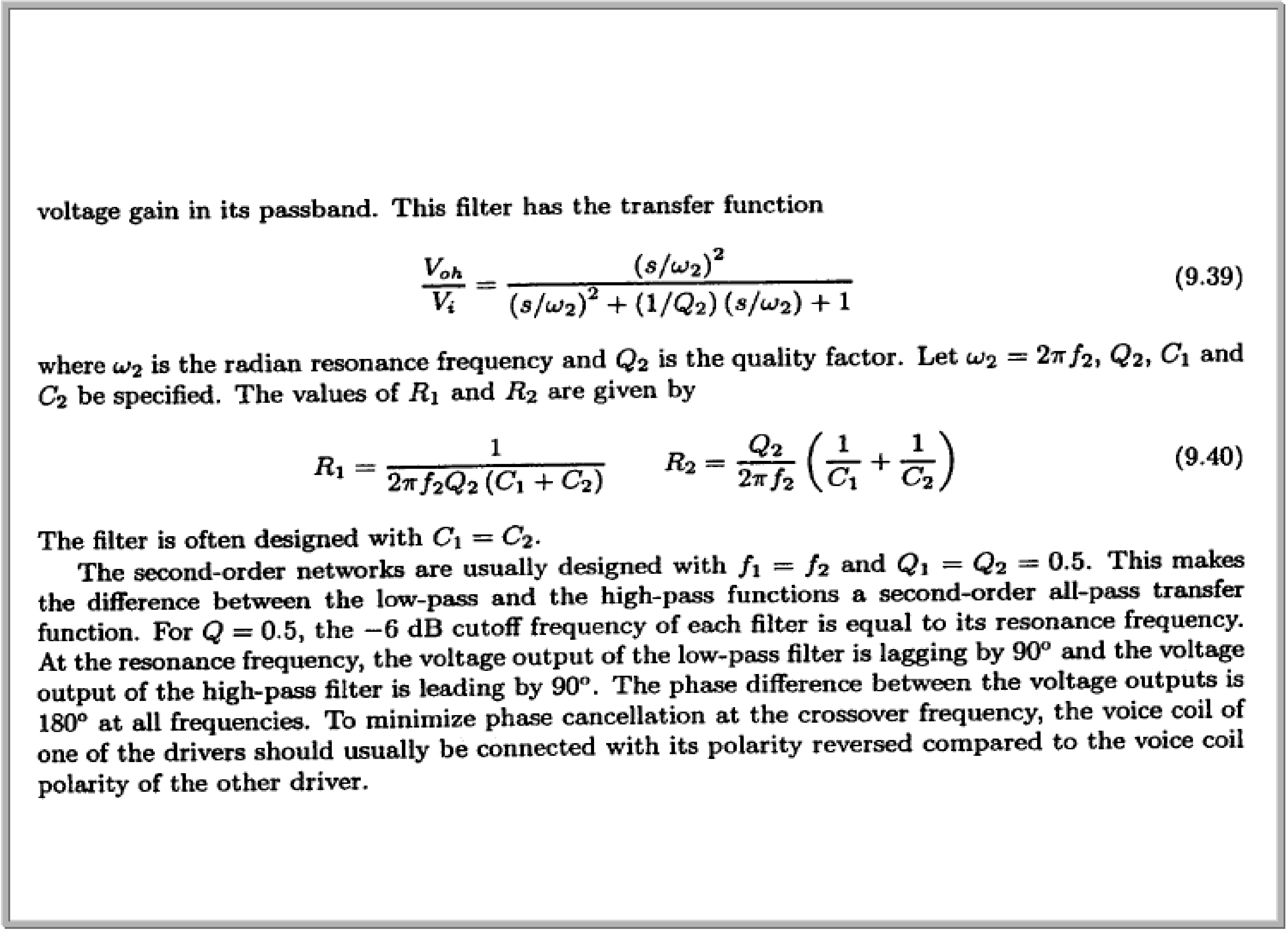


Figure 9.14: Second-order Sallen-Key (a) low-pass and (b) high-pass filters.

Figure 9.14(b) shows the circuit diagram of a second-order Sallen-Key high-pass filter with unity



voltage gain in its passband. This filter has the transfer function

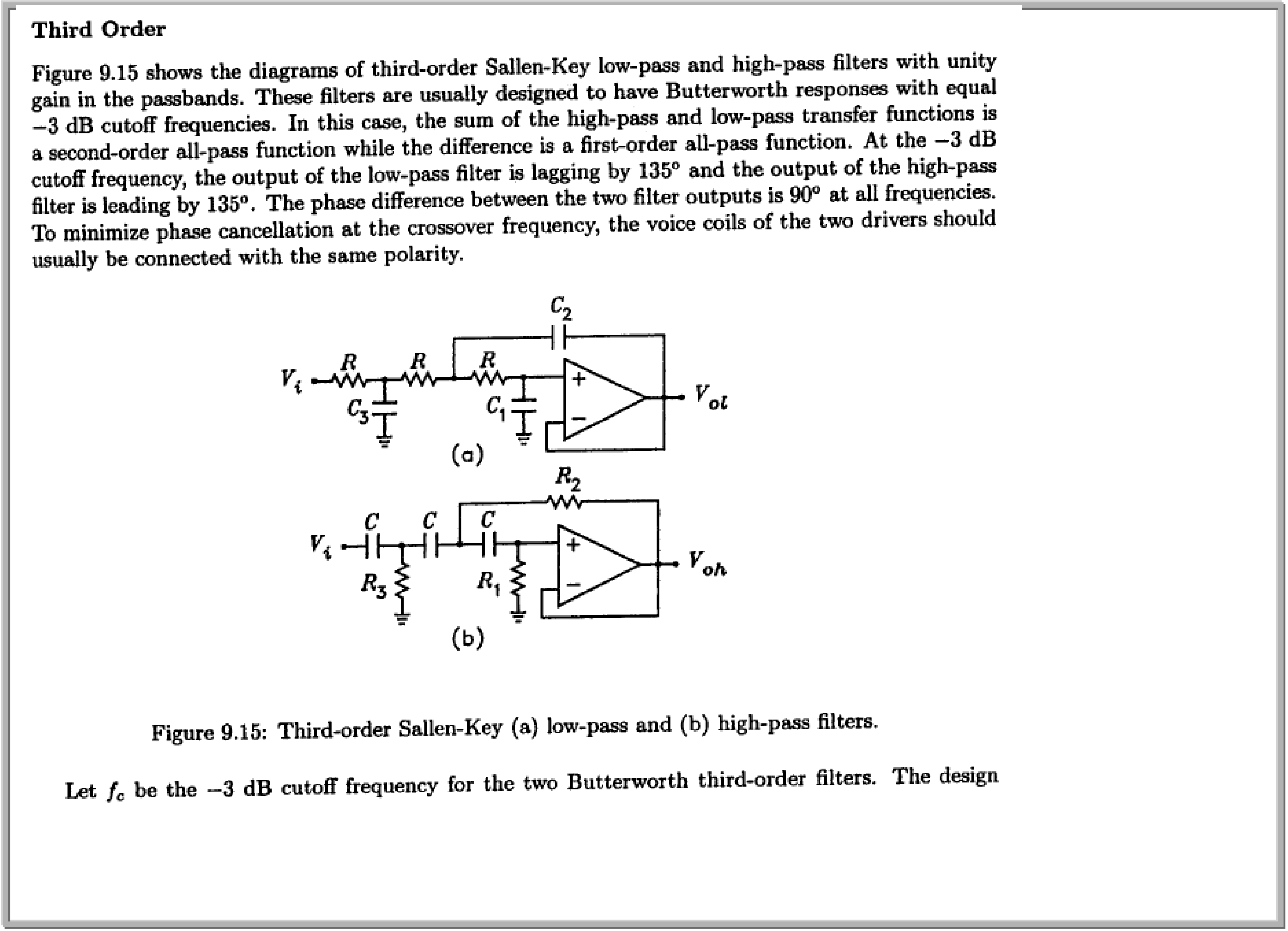
$$\frac{V_{oh}}{V_i} = \frac{(s/\omega_2)^2}{(s/\omega_2)^2 + (1/Q_2)(s/\omega_2) + 1} \tag{9.39}$$

where ω_2 is the radian resonance frequency and Q_2 is the quality factor. Let $\omega_2 = 2\pi f_2$, Q_2, C_1 and C_2 be specified. The values of R_1 and R_2 are given by

$$R_1 = \frac{1}{2\pi f_2 Q_2 (C_1 + C_2)} \qquad R_2 = \frac{Q_2}{2\pi f_2}\left(\frac{1}{C_1} + \frac{1}{C_2}\right) \tag{9.40}$$

The filter is often designed with $C_1 = C_2$.

The second-order networks are usually designed with $f_1 = f_2$ and $Q_1 = Q_2 = 0.5$. This makes the difference between the low-pass and the high-pass functions a second-order all-pass transfer function. For $Q = 0.5$, the -6 dB cutoff frequency of each filter is equal to its resonance frequency. At the resonance frequency, the voltage output of the low-pass filter is lagging by 90^o and the voltage output of the high-pass filter is leading by 90^o. The phase difference between the voltage outputs is 180^o at all frequencies. To minimize phase cancellation at the crossover frequency, the voice coil of one of the drivers should usually be connected with its polarity reversed compared to the voice coil polarity of the other driver.

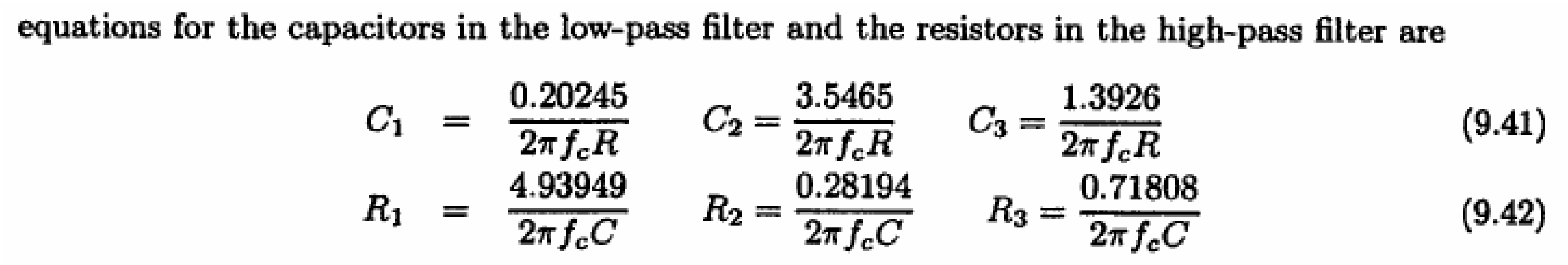


Third Order

Figure 9.15 shows the diagrams of third-order Sallen-Key low-pass and high-pass filters with unity gain in the passbands. These filters are usually designed to have Butterworth responses with equal −3 dB cutoff frequencies. In this case, the sum of the high-pass and low-pass transfer functions is a second-order all-pass function while the difference is a first-order all-pass function. At the −3 dB cutoff frequency, the output of the low-pass filter is lagging by 135° and the output of the high-pass filter is leading by 135°. The phase difference between the two filter outputs is 90° at all frequencies. To minimize phase cancellation at the crossover frequency, the voice coils of the two drivers should usually be connected with the same polarity.

Figure 9.15: Third-order Sallen-Key (a) low-pass and (b) high-pass filters.

Let f_c be the −3 dB cutoff frequency for the two Butterworth third-order filters. The design



equations for the capacitors in the low-pass filter and the resistors in the high-pass filter are

$$C_1 = \frac{0.20245}{2\pi f_c R} \qquad C_2 = \frac{3.5465}{2\pi f_c R} \qquad C_3 = \frac{1.3926}{2\pi f_c R} \tag{9.41}$$

$$R_1 = \frac{4.93949}{2\pi f_c C} \qquad R_2 = \frac{0.28194}{2\pi f_c C} \qquad R_3 = \frac{0.71808}{2\pi f_c C} \tag{9.42}$$