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PEAK CURRENT REQUIREMENT OF COMMERCIAL LOUDSPEAKER SYSTEMS

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Abstract

Measured terminal impedances of several commercial loudspeaker systems are developed into their equivalent electrical circuits by using the Brune network synthesis method. The synthesized circuits accurately describe the properties of the load as seen by the amplifier feeding the loudspeaker system.

A group of non-sinusoidal audio signal sequences, which cause the loudspeaker system to draw momentary currents considerably in excess of what could be expected from the rated terminal impedance is identified using computerized network analysis methods. The maximum value of peak current reported for a commercial loudspeaker system is 6.6 times larger than that of an eight ohm resistor. The current peaks typically last a few hundred microseconds.

The current peaks are caused by simultaneous parallel excitation of several of the drivers of a multiway system, by summation of cancellation currents originating from the energy stored in the mechanical and electrical reactances of the circuit, and by impedance transformation effects in the crossover network.

The results imply that for short periods of time an amplifier should be able to drive, with full output voltage swing and without appreciable distortion, loads equal to a resistor of one ohm.

INTRODUCTION

A loudspeaker has a rated impedance, typically 8 ohms. International standards prescribe that a loudspeaker may not exhibit less than 80 % (i.e., 6.3 ohms) of its rated impedance in any part of its rated frequency range. The same standards prescribe that the performance of an amplifier is to be measured using a purely resistive rated load, normally 8 ohms (1).

Typical measured loudspeaker impedance plots show minima of 4 ohms or less, some dipping below 2 ohms. Moreover, loudspeakers exhibit highly reactive behaviour with typical impedance phase angle ranges of -60 to +60 degrees. Most commercial audio power amplifiers have seemingly been designed and tested using only the rated resistive load and exhibit gross harmonic distortion and/or severely reduced output voltage when driving complex loads resembling real-life loudspeakers (2).

The above measurements were performed using a sinusoidal signal, thereby exciting one driver of a multiway loudspeaker system only. However, a complex load such as a loudspeaker behaves markedly differently when excited with non-sinusoidal signals. Considerably larger current drains than those for a resistive load have been measured and reported elsewhere (3-6). To make the simplest possible illustration, consider a resistor and symmetrical square-wave voltage excitation. Then connect a capacitor in series with the resistor. The peak current drawn by the network will increase to twice the current drawn by the resistor alone, even though the "impedance" of the circuit has increased.

The worst excitation signals reported have been variable-length square-wave sequences (3). Experimental search of the signal sequences is time-consuming, and a more analytical procedure would be welcome. The purpose of this paper is to demonstrate such a method.

LOUDSPEAKER IMPEDANCE MODELLING

Loudspeaker equivalent circuits have usually been derived from driver mechanical parameters by using electro-mechanical analogy. This method is inaccurate because it neglects the influence of the cabinet and many electrically relevant second-order driver parameters, and also makes the analysis of the cross-over network difficult. A more accurate method is to measure the terminal impedance of the loudspeaker and to derive the electrical equivalent circuit by using network synthesis methods.

Three popular three-way loudspeaker systems were analyzed; Infinity Rsb, Yamaha NS 1000 M, and Heco Phon 3. The measurements were performed at 1 volt (rms) excitation level and the results therefore represent the linear operating region of the loudspeakers. The loudspeaker terminal impedances were measured for the woofer, the midrange, and the tweeter separately by dissecting the cross-over network at the speaker system terminals. This method partitions the loudspeaker system into three subsystems, each including the respective driver and its part of the cross-over network. The measurement system is depicted in Fig. 1.

The measured impedance plots were synthesized into driving point impedance polynomials by using partial fraction expansions (7). In this procedure, the modulus of the impedance and its phase were iteratively matched to the polynomial with an accuracy of 10 % or better, and the zero-phase points were matched with an accuracy better than two degrees. The resulting impedance polynomials are given in Appendix 1.

EQUIVALENT CIRCUIT SYNTHESIS

The equivalent circuits were synthesized from the calculated impedance polynomials by first performing a Foster resistance reduction preamble and a Cauer cycle, where necessary, and thereafter performing successive Brune network synthesis cycles until the synthesis procedure terminated (7). This method realizes all positive real functions with real components, and although the synthesized circuit does not necessarily resemble the actual circuit physically, it behaves electrically in the same way.

The resulting equivalent circuits are shown in Figs. 2-4. They are much more complicated than expected and contain all the effects of the cross-over network, the possible driver anomalies, and the reflected acoustic properties of the cabinet. In order to check the validity of the synthesized circuits, their impedance plots were calculated using the SPICE network analysis program run on a VAX 11/730. The results are shown in Appendix 2 along with the original measured impedances, indicating an almost perfect match.

Characteristic findings from the synthesized equivalent circuits can be summarized as follows:

* Some of the equivalent circuits are not realizable without transformers.

* In some cases the series arm resistance of the equivalent circuit is smaller than the driver voice coil resistance. This is probably caused by the cross-over circuit reactances acting as step-down impedance transformers (as in RF tuning circuits). It is possible that the designer has inadvertently used this effect to equalize the efficiencies of the drivers.

WORST-CASE EXCITATION SIGNALS

Using the synthesized equivalent circuits and the NAP-2 circuit analysis program run on a Univac 1100/22 computer, a search for a worst-case excitation signal was conducted. The first phase was to determine such a voltage excitation which would maximize the current into a single driver. To make certain that the signal was legitimate and realistic, it was bandwidth-limited to 20 Hz - 20 kHz and its maximum rise time set to 5 μs. All the signals were normalized to 1 volt peak amplitude. The following signal shapes were tested on each equivalent circuit:

1. Half-cycle of a sinusoid, which is a realistic acoustical signal.

2. Sin^2-pulse, which is a realistic acoustical impulse.

3. Rise-time-limited step, which is a realistic acoustical transient.

4. Combination of a step and a half-sine.

5. Non-periodic sequence of steps of equal but opposite polarity.

The basic computational procedure was to feed one signal element into the equivalent circuit while observing the current flow into the circuit. At a suitable moment, the next signal element with either the same or opposite polarity was fed into the circuit so as to increase the peak current. This procedure was repeated a few times until the peak current no longer increased. Fig. 5 shows a typical excitation sequence for one of the drivers, indicating the way the current builds up during successive properly timed voltage steps. Table 1 lists the peak currents for each signal and driver separately. The worst signals for all drivers turned out to be step sequences with variable timing.

The equivalent circuit for the complete loudspeaker system was then created by connecting the three separate circuits in parallel. The worst-case signal was synthesized by exciting the woofer section with its maximum-current signal and then adding first the midrange and thereafter the tweeter signals. The summation was carried out so that the peak voltage of the excitation signal remained at 1 volt. The worst-case signals for each of the loudspeaker systems are shown in Figs. 6-8, and the maximum system currents are listed in Table 2. The Table also shows how much larger the loudspeaker system current is as compared to the current into an 8 ohm resistor excited with the same signal. The typical duration of the peak current is 50 to 200 microseconds, i.e., not short in comparison to acoustical impulses in general.

CONCLUSIONS

It has been shown that commercial loudspeaker systems may, under suitable excitation, draw current considerably in excess of what could be deduced from their rated impedance. The maximum current found is 6.6 times larger than that drawn by an eight ohm resistor with the same excitation signal. The peak currents typically last for 50-200 microseconds.

The worst-case signals causing the excessive currents are bandwidth- and voltage-limited sequences of non-periodic steps. Similar behaviour, although with smaller peak currents, can be found using properly timed sequences of sin- and sin -pulses. All of these are fully legitimate as acoustical and musical signals. Every loudspeaker has an individual worst-case timing sequence, and no universally applicable test signal has been identified.

In order to prevent gross distortion during musical passages resembling this type of signal, the audio power amplifier must be capable of delivering linearily short-term currents into the load as if the amplifier were driving a one-ohm resistor.

ACKNOWLEDGEMENTS

The authors are grateful for the insights and constructive criticism of Ilpo Martikainen and Ari Varla of Genelec Inc., Iisalmi, Finland, and for the numerous detailed discussions with Mamoru Sekiya and Marty Zanfino of Harman/Kardon Inc., New York, USA. University of Oulu, Finland, is gratefully acknowledged for the use of about hundred hours of their prime computer CPU time.

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(7) Weinberg, L., Network analysis and synthesis. McGraw-Hill, New York 1962, 692 p.

TABLE 1. Peak current into each driver for various excitation signals. Signals are two half-sine pulses, two $\sin^2$-pulses, step, step + half-sine, and step sequence. Excitation voltage is 1 volt peak.

LOUDSPEAKER	DRIVER	CURRENT IN mA AT 1 VOLT EXCITATION				
		sin	$\sin^2$	step	step +sin	step seq
Infinity	woofer	249	230	206	316	462
	midrange	115	112	239	124	288
	tweeter	460	436	461	440	576
Yamaha	woofer	161	156	109	207	327
	midrange	129	126	272	138	301
	tweeter	208	190	230	208	278
Heco	woofer	231	230	201	286	356
	midrange	168	149	201	181	235
	tweeter	338	296	387	343	404

TABLE 2. Peak currents into loudspeaker systems for the worst-case step sequence. Excitation voltage is +/- 1 volt. "Multiplier" indicates how much more current the loudspeaker draws than an 8 ohm resistor for the same signal.

LOUDSPEAKER SYSTEM	CURRENT PEAK mA	MULTIPLIER re 8 ohm res
8 ohm resistor	125	1.0
Infinity	830	6.6
Yamaha	476	3.8
Heco	637	5.1

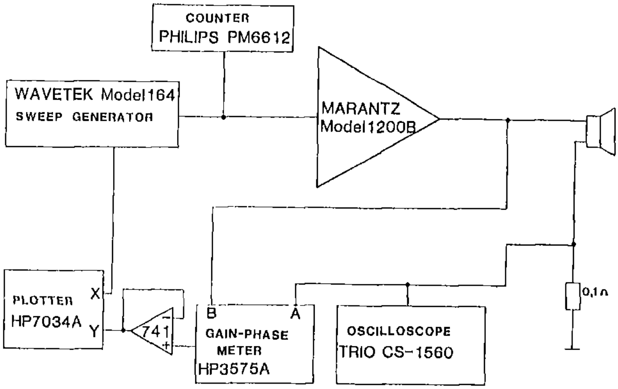
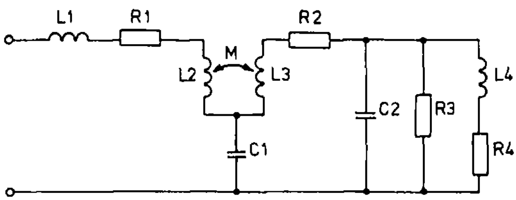


Fig. 1. Setup used to measure the impedance plots.



R1 = 1.080 Ω

R2 = 2.405 Ω

R3 = 11.392 Ω

R4 = 25.101 mΩ

C1 = 133.374 μF

C2 = 1527.836 μF

L1 = 2.363 mH

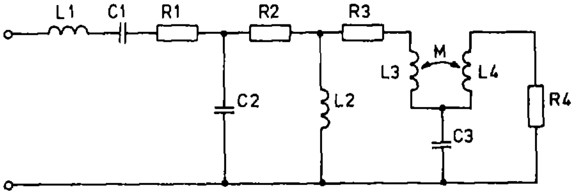
L2 = 24.512 μH

L3 = 0.709 mH

L4 = 4.408 mH

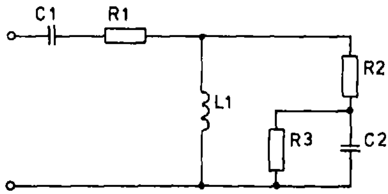
M = 0.132 mH

Fig. 2a. Synthesized equivalent circuit for Infinity Rsb woofer.



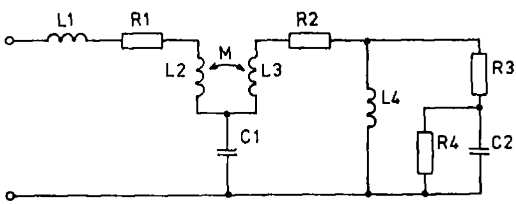
R1 = 3.565Ω	C1 = 17.328 μF	L1 = 0.367 mH
R2 = 0.256Ω	C2 = 40.661 μF	L2 = 0.126 mH
R3 = 2.225Ω	C3 = 166.859 μF	L3 = 0.602 μH
R4 = 0.109 Ω		L4 = 18.515 μH
		M = 3.339 μH

Fig. 2b. Synthesized equivalent circuit for Infinity Rsb midrange.



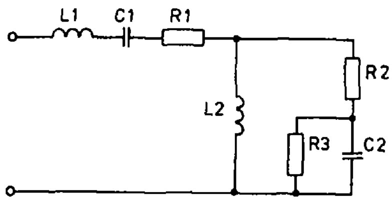
R1 = 0,798 Ω	C1 = 7.650 μF	L1 = 65.019 μH
R2 = 3.375 Ω	C2 = 2.444 μF	
R3 = 0,640 Ω		

Fig. 2c. Synthesized equivalent circuit for Infinity Rsb tweeter.



R1 = 1.756Ω	C1 = 142.846 μF	L1 = 4.927 mH
R2 = 3.172Ω	C2 = 674.826 μF	L2 = 19.976 μH
R3 = 1.298Ω		L3 = 1.163 mH
R4 = 169.604Ω		L4 = 20.642 mH
		M = 0.152 mH

Fig. 3a. Synthesized equivalent circuit for Yamaha NS 1000 M woofer.

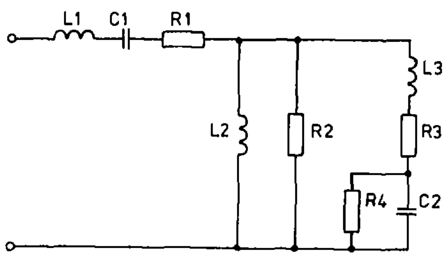


R1 = 3.766 Ω
R2 = 0.577 Ω
R3 = 2.097 Ω

C1 = 27.225 μF
C2 = 37.740 μF

L1 = 0.258 mH
L2 = 0.334 mH

Fig. 3b. Synthesized equivalent circuit for Yamaha NS 1000 M midrange.

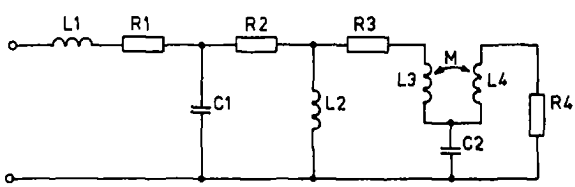


R1 = 2.697 Ω
R2 = 9.146 Ω
R3 = 5.053 Ω
R4 = 171.751 Ω

C1 = 2.713 μF
C2 = 2.621 μF

L1 = 4.095 μH
L2 = 78.935 μH
L3 = 0.247 mH

Fig. 3c. Synthesized equivalent circuit for Yamaha NS 1000 M tweeter.

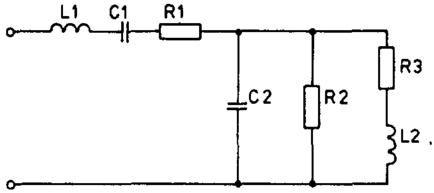


R1 = 1.074 Ω
R2 = 2.723 Ω
R3 = 0.105 Ω
R4 = 11.235 Ω

C1 = 43.355 μF
C2 = 1204.899 μF

L1 = 1.275 mH
L2 = 2.608 mH
L3 = 0.319 mH
L4 = 0.379 mH
M = 0.348 mH

Fig. 4a. Synthesized equivalent circuit for Heco Phon 3 woofer.

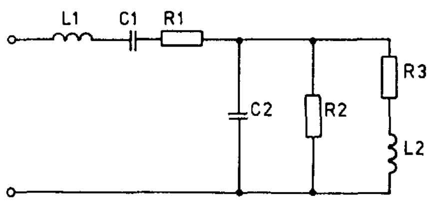


R1 = 5.486 Ω   C1 = 8.863 μF   L1 = 0.231 mH

R2 = 6.549 Ω   C2 = 1232.049 μF   L2 = 11.357 μH

R3 = 44.467 mΩ

Fig. 4b. Synthesized equivalent circuit for
Heco Phon 3 midrange.



R1 = 2.616 Ω   C1 = 7.197 μF   L1 = 11.884 μH

R2 = 2.856 Ω   C2 = 0.729 μF   L2 = 20.276 μH

R3 = 0.227 Ω

Fig. 4c. Synthesized equivalent circuit for
Heco Phon 3 tweeter.

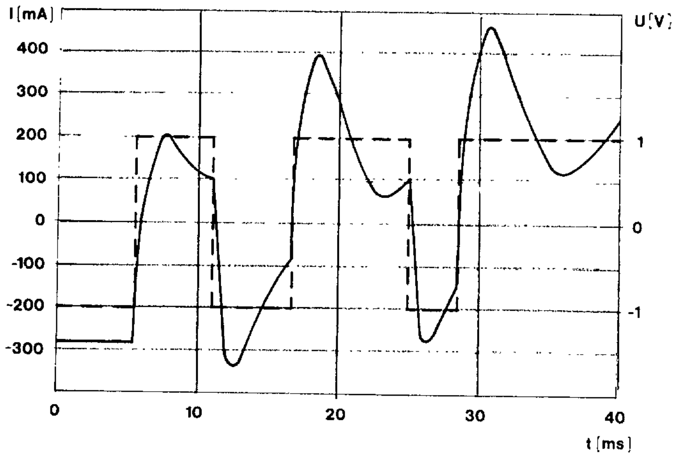


Fig. 5. Current response (solid line) of Infinity Rsb woofer to a step sequence excitation of 1 volt (dotted line).

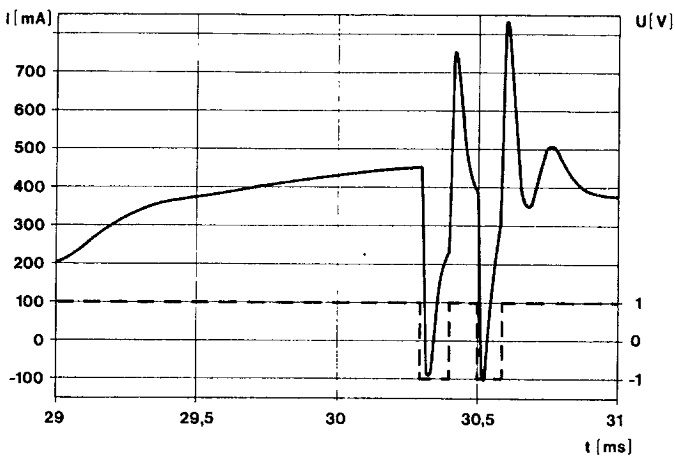


Fig. 6. Current response (solid line) of Infinity Rsb to a worst-case step sequence excitation of 1 volt (dotted line).

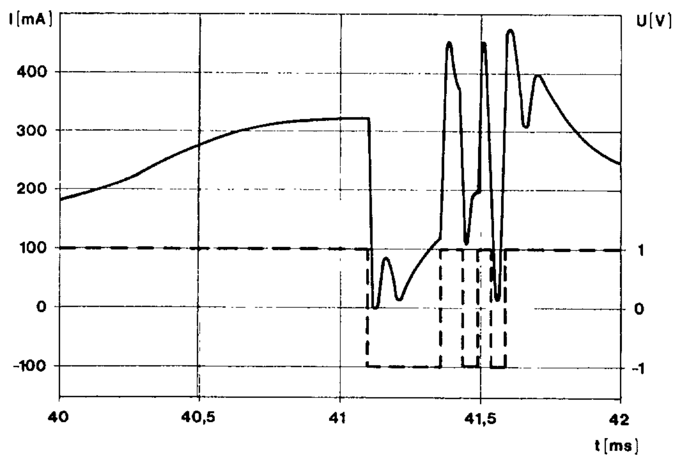


Fig. 7. Current response (solid line) of Yamaha NS 1000 M to a worst-case step sequence excitation of 1 volt (dotted line).

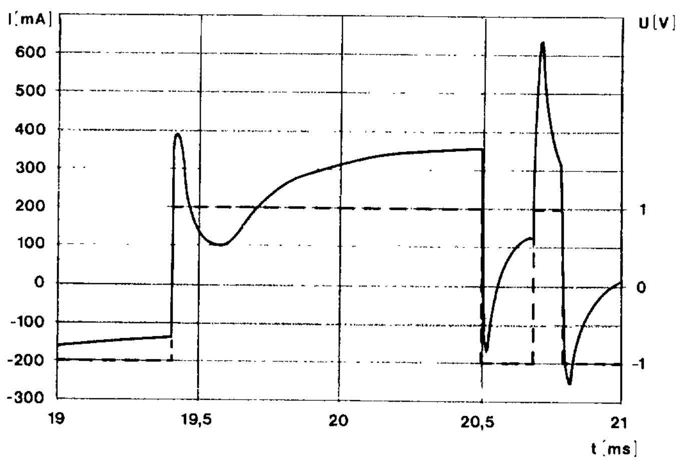


Fig. 8. Current response (solid line) of Heco Phon 3 to a worst-case step sequence excitation of 1 volt (dotted line).

APPENDIX 1

HECO Phon 3 **WOOFER**

$$Z(s) = 1{,}275\cdot 10^{-3}\,\frac{s^5 + 1{,}036\cdot 10^4 s^4 + 9{,}143\cdot 10^7 s^3 + 2{,}017\cdot 10^{11} s^2 + 7{,}516\cdot 10^{13} s + 5{,}325\cdot 10^{16}}{s^4 + 9{,}516\cdot 10^3 s^3 + 6{,}531\cdot 10^7 s^2 + 8{,}465\cdot 10^9 s + 1{,}788\cdot 10^{13}}$$

MIDRANGE

$$Z(s) = 2{,}309\cdot 10^{-4}\,\frac{s^4 + 2{,}780\cdot 10^4 s^3 + 7{,}255\cdot 10^8\, s^2 + 3{,}711\cdot 10^{12} s + 3{,}516\cdot 10^{16}}{s(s^2 + 4{,}039\cdot 10^3 s + 7{,}195\cdot 10^7)}$$

TWEETER

$$Z(s) = 1{,}188\cdot 10^{-5}\,\frac{s^4 + 7{,}113\cdot 10^5 s^3 + 3{,}082\cdot 10^{11} s^2 + 2{,}310\cdot 10^{16} s + 8{,}535\cdot 10^{20}}{s(s^2 + 4{,}912\cdot 10^5 s + 7{,}300\cdot 10^{10})}$$

APPENDIX 1. SYNTHESIZED IMPEDANCE POLYNOMIALS FOR THE DRIVERS

INFINITY Rsb **WOOFER**

$$Z(s) = 2{,}363\cdot 10^{-3}\,\frac{s^5 + 3{,}947\cdot 10^3 s^4 + 4{,}736\cdot 10^8 s^3 + 5{,}355\cdot 10^{11} s^2 + 6{,}041\cdot 10^{12} s + 2{,}342\cdot 10^{15}}{s^4 + 3{,}455\cdot 10^3 s^3 + 4{,}778\cdot 10^8 s^2 + 1{,}178\cdot 10^9 s + 1{,}582\cdot 10^{12}}$$

MIDRANGE

$$Z(s) = 3{,}668\cdot 10^{-4}\,\frac{s^6 + 2{,}894\cdot 10^4 s^5 + 9{,}955\cdot 10^8 s^4 + 1{,}449\cdot 10^{13} s^3 + 2{,}248\cdot 10^{17} s^2 + 1{,}428\cdot 10^{21} s + 9{,}306\cdot 10^{24}}{s(s^4 + 1{,}922\cdot 10^4 s^3 + 5{,}843\cdot 10^8 s^2 + 5{,}162\cdot 10^{12} s + 5{,}914\cdot 10^{16})}$$

TWEETER

$$Z(s) = 4{,}173\,\frac{s^3 + 7{,}785\cdot 10^5 s^2 + 2{,}920\cdot 10^{10} s + 1{,}237\cdot 10^{15}}{s(s^2 + 6{,}912\cdot 10^5 s + 3{,}984\cdot 10^{10})}$$

YAMAHA NS 1000 M **WOOFER**

$$Z(s) = 4{,}927\cdot 10^{-3}\,\frac{s^5 + 4{,}286\cdot 10^3 s^4 + 1{,}004\cdot 10^7 s^3 + 8{,}864\cdot 10^9 s^2 + 2{,}842\cdot 10^{12} s + 4{,}373\cdot 10^{14}}{s^4 + 3{,}914\cdot 10^3 s^3 + 7{,}570\cdot 10^6 s^2 + 6{,}293\cdot 10^8 s + 4{,}383\cdot 10^{11}}$$

MIDRANGE

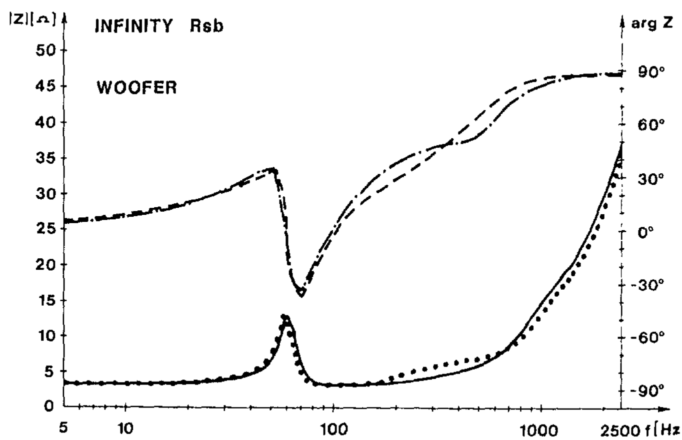
$$Z(s) = 2{,}581\cdot 10^{-4}\,\frac{s^4 + 3{,}119\cdot 10^4 s^3 + 5{,}839\cdot 10^8 s^2 + 3{,}519\cdot 10^{12} s + 1{,}438\cdot 10^{16}}{s(s^2 + 1{,}436\cdot 10^4 s + 1{,}011\cdot 10^8)}$$

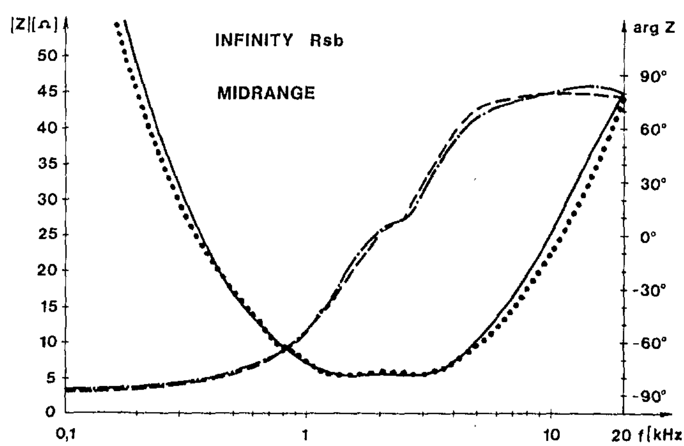
TWEETER

$$Z(s) = 4{,}095\cdot 10^{-6}\,\frac{s^5 + 3{,}215\cdot 10^6 s^4 + 7{,}174\cdot 10^{11} s^3 + 8{,}560\cdot 10^{16} s^2 + 4{,}187\cdot 10^{21} s + 1{,}507\cdot 10^{26}}{s(s^3 + 3{,}231\cdot 10^5 s^2 + 3{,}426\cdot 10^{10} s + 1{,}674\cdot 10^{15})}$$

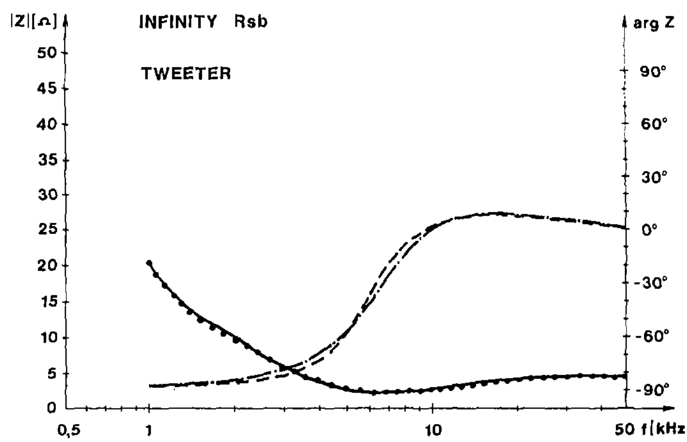
ıPPENDIX 2 a. MEASURED AND CALCULATED IMPEDANCE AND PHASE PLOTS
Measured values are from actual measurements using the setup of Fig. 1. Calculated values are from synthesized equivalent circuits shown in Appendix 1.

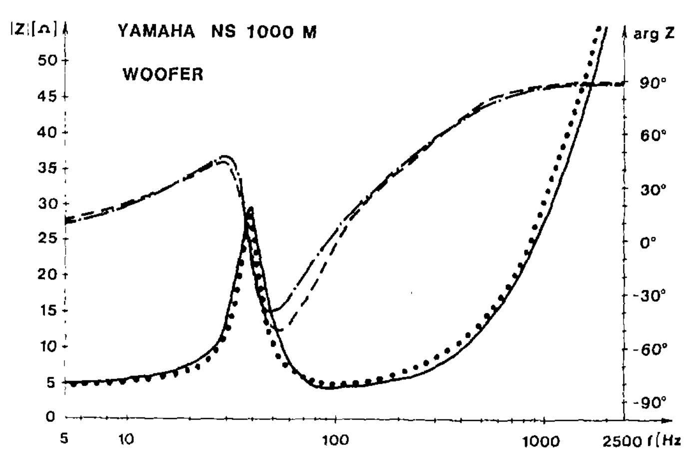
Measured modulus of impedance	————
Measured phase of impedance	– – – –
Calculated modulus of impedance	· · · · ·
Calculated phase of impedance	–·–·–·–



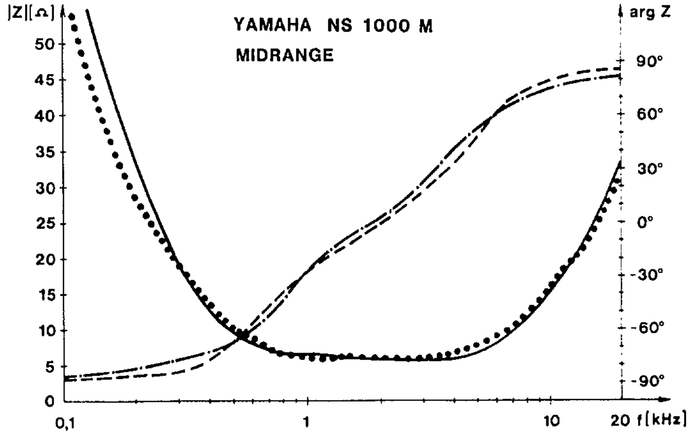


APPENDIX 2b.

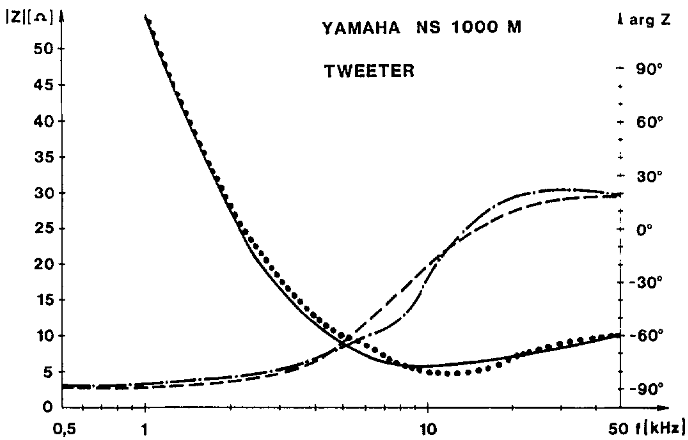

|Z|[Ω]
INFINITY Rsb
TWEETER
arg Z
50
45
40
35
30
25
20
15
10
5
0
90°
60°
30°
0°
-30°
-60°
-90°
0,5
1
10
50 f[kHz]


|Z|[Ω]
YAMAHA NS 1000 M
WOOFER
arg Z
50
45
40
35
30
25
20
15
10
5
0
90°
60°
30°
0°
-30°
-60°
-90°
5
10
100
1000
2500 f[Hz]

APPENDIX 2c.

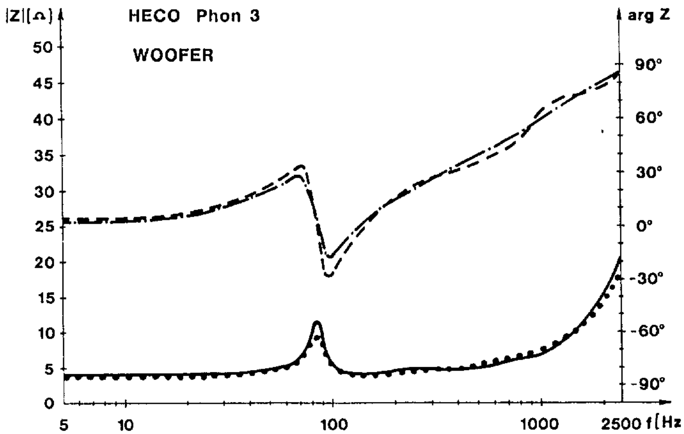


|Z|[Ω]
YAMAHA NS 1000 M
MIDRANGE
arg Z
50
45
40
35
30
25
20
15
10
5
0
90°
60°
30°
0°
-30°
-60°
-90°
0,1
1
10
20 f[kHz]

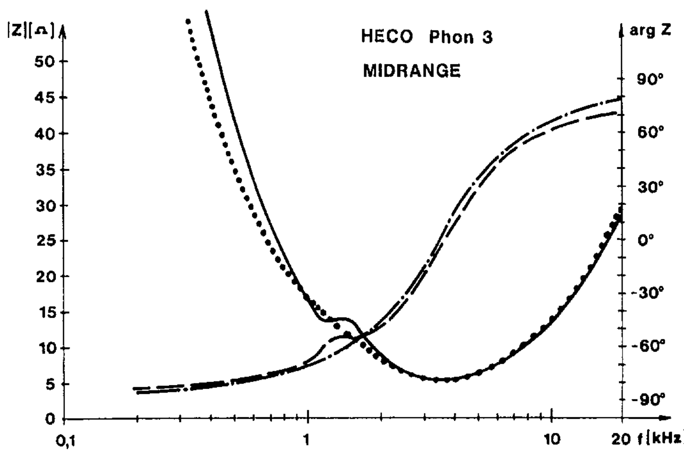


|Z|[Ω]
YAMAHA NS 1000 M
TWEETER
arg Z
50
45
40
35
30
25
20
15
10
5
0
90°
60°
30°
0°
-30°
-60°
-90°
0,5
1
10
50 f[kHz]

APPENDIX 2d.

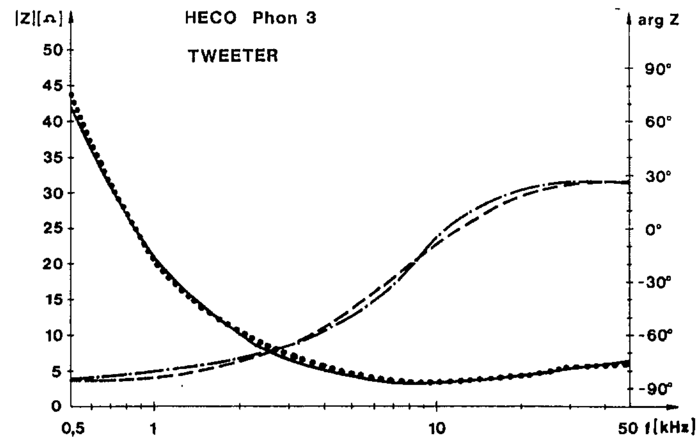


|Z|[Ω]
HECO Phon 3
WOOFER
arg Z
50
45
40
35
30
25
20
15
10
5
0
90°
60°
30°
0°
-30°
-60°
-90°
5
10
100
1000
2500 f[Hz]



|Z|[Ω]
HECO Phon 3
MIDRANGE
arg Z
50
45
40
35
30
25
20
15
10
5
0
90°
60°
30°
0°
-30°
-60°
-90°
0,1
1
10
20 f[kHz]

APPENDIX 2e.



|Z|[Ω]
HECO Phon 3
TWEETER
arg Z
50
45
40
35
30
25
20
15
10
5
0
90°
60°
30°
0°
-30°
-60°
-90°
0,5
1
10
50 f[kHz]