Comparative Measurements on Loudspeaker Distortion: Current vs. Voltage Control

Esa MERILÄINEN

Eerikinkallio 4 A 8, FI-02400 Kirkkonummi, Finland

Modulation and harmonic distortion produced by ordinary moving-coil direct-radiator drive units are measured under current control and voltage control. A realistic two-tone test signal is used to investigate the detrimental effect of the voice coil electromotive forces on the voltage-to-current conversion that is critical with voltage control. Dramatic improvements in distortion performance are obtained with current control. Current nonlinearities in voltage-controlled speakers are shown to be the dominant source of modulation and odd harmonic distortions at signal frequencies above the fundamental resonance region. Currents in conductive voice coil formers also seem to be significant sources of distortion; with current control and non-conductive formers, odd harmonics and related modulation products virtually vanished in the upper midrange.

1. Introduction

Everywhere in the world, loudspeakers used for sound reproduction are driven by voltage-output power amplifiers without noteworthy exceptions. However, the source impedance seen by a moving-coil drive unit is an important factor in determining its performance; not only in terms of frequency response but also regarding distortion (MILLS, HAWKSFORD, 1989; MERILÄINEN, 2010). The latter is because the driving force is determined by current, and the electromotive forces (EMF voltage components), that appear in series with the voice coil resistance, introduce nonlinearity in the relationship between the voice coil voltage and current. When the source impedance is much lower than the driver (load) impedance, we may talk about voltage control (henceforth VC), as the quantity that is forced is voltage; and conversely, when the source impedance is much higher than the driver impedance, we force current and may call it current control (henceforth CC) or current drive. General introduction to nonlinear distortions can be found in (DOBRUCKI, 2011).

The electrical equivalent circuit of a speaker driver, for the purposes of this study, is presented in Fig. 1 and is valid for all enclosure types. R_c denotes the voice coil DC resistance, Z_m denotes the motional impedance due to the motional EMF (E_m), Z_i denotes
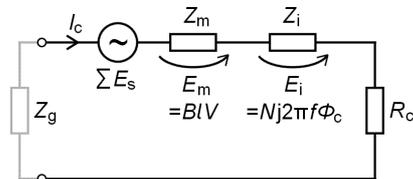

Fig. 1. Electrical equivalent circuit for a speaker driver.

the inductive impedance due to the voice coil's self-inductance EMF (E_i), while Z_g represents the source impedance seen by the driver (the actual source, voltage or current, is not shown). Here, Z_m and Z_i are considered as pure linear impedances, and the nonlinearities that they actually introduce, as well as possible microphonic interferences, are represented by the spurious EMF sources E_s.

E_m is the product of the force factor Bl (magnetic flux density times wire length immersed in the field) and velocity V and comes 90° behind diaphragm acceleration and the pressure radiated (DOBRUCKI, 2011, p. 449). In the mass-controlled region (i.e. above system resonance), that is of interest in this study, the dominant mechanical counter-force is due to the inertia of the moving mass. Therefore, we can write for the driving force:

$$F = BlI_c \approx mA = mj2\pi f\,V, \qquad (1)$$

where A is diaphragm acceleration and m is the moving mass. The last equality is because differentiation in the time domain corresponds to multiplication by $j2\pi f$ in the phasor domain. Then we get for the motional impedance:

$$Z_m = \frac{BlV}{I_c} \approx \frac{(Bl)^2}{mj2\pi f}. \tag{2}$$

Z_m is thus capacitive (angle $-90°$) and basically inversely proportional to frequency above the system resonance region. This also means that E_m is in phase quadrature with the current, as well as with the acceleration and the pressure (though it is often called "back" EMF). The approximation of Eq. (2) is valid only as high in frequency as the pistonic operation extends. Beyond that point, Z_m and E_m become rather unpredictable while still retaining considerable magnitude.

The inductance EMF, E_i, arises directly from Faraday's law which states that the EMF induced in a loop of wire equals the rate of change of the magnetic flux (Φ_c) flowing through the loop. E_i is thus basically directly proportional to frequency but in practice much more gradual due to eddy current losses in the pole pieces.

Voice coil inductance exhibits nonlinearity in two basic ways: by dependence on coil position and on current (KLIPPEL, 2006). The inductance's dependence on the displacement x introduces an inherently nonlinear spurious EMF that can be expressed as (DOBRUCKI, 2011, p. 449)

$$e_{s,\,dL/dx} = v\frac{dL_c}{dx}i_c, \tag{3}$$

where L_c is the effective voice coil inductance at the frequencies of interest. Since the velocity, v, is about inversely proportional to frequency (Eq. (2)), and L_c also decreases with frequency, this nonlinearity EMF is most significant at low frequencies. In case that dL_c/dx is constant within the displacement range excited, the resulting distortion is of 2nd order.

The spurious EMF generated by the inductance's dependence on current can be expressed as (DOBRUCKI, 2011, p. 449)

$$e_{s,\,dL/di} = \frac{di_c}{dt}\frac{dL_c}{di_c}i_c. \tag{4}$$

This doesn't yet take into account hysteresis effects. As di_c/dt is, in principle, directly proportional to frequency and L_c decreases somewhat with frequency, this EMF component increases gradually with frequency.

It is worth noting that Z_m and Z_i are of almost opposite phase and therefore partially cancel each other in the driver's total impedance. This cancellation is typically greatest in the 300 Hz region where the magnitudes of Z_m and Z_i become equal. The spurious EMF components pertaining to both are, however, generally not canceled.

The nonlinearities themselves between the voice coil voltage and current cannot be reduced with any source impedance (Z_g), and thus spurious EMF voltage components (E_s) will always be generated at frequencies that are harmonic multiples or integer-coefficient combinations of the signal frequencies. How much current and hence acoustic distortion these EMF components are then able to produce is determined by the total impedance seen by them at their respective frequencies. On pure VC ($Z_g = 0$), this attenuating impedance consists of only the driver's own impedance ($R_c + Z_m + Z_i$), whereas on CC it can be made effectively infinite. Considering the nonlinear EMF distortions, the source impedance (Z_g) at the signal frequency is thus actually unimportant, while the impedance at the distortion product frequencies is all-important. This fact also gives us more liberty to tailor the source impedance in the bass region when needed since the most material EMF distortion products fall higher in frequency.

Due to the simple inverse relationship between total load circuit impedance and the EMF-derived distortion, appreciable improvement is gained already at intermediate source impedances. For example, when the source impedance equals the driver impedance (magnitude & phase), the reduction in the EMF-derived distortion will be 6 dB compared with pure VC. Thus, CC is a feasible principle also for passive loudspeakers, where the crossover components compromise the source impedance of each driver, irrespective of whether VC or CC is pursued.

While it is obvious that CC doesn't eliminate the well-known force factor ($Bl(x)$) and suspension nonlinearities or the solenoid (reluctance) force, this study focuses on comparing modulation distortion at frequencies where cone displacement is not yet large and with signal levels carefully matched between the two driving modes at each frequency. Thus, there becomes well exposed the severe yet largely overlooked distortion arising from the V/I conversion in the voltage-controlled speaker. This gives some insight into the unfortunate consequences to nearly all sound reproduction, caused by the unsuspectingly adopted, universal custom of VC.

2. Background

There can be found very little published acoustical measurements that compare the nonlinear distortion between the two operation modes, especially above the bass region. Actual measurements are, however, needed here since the most detrimental nonlinearity of the V/I conversion, current dependency of inductance, is difficult to model. In (MILLS, HAWKSFORD, 1989), some comparison was carried out, but the har-

monics measurement comprised only two frequencies from one driver; and the intermodulation test signal used, that consisted of bass and middle tones (50 Hz & 1000 Hz) in equal proportion, revealed only a few decibels decrease in the modulation products on CC. In (BORTONI *et al.*, 2007, p. 13), the THD of a 8-in woofer was compared over the whole range, showing remarkable improvement on CC between 70 and 700 Hz despite that due to differing signal levels the test is unfair to CC.

Virtually all speaker distortion studies available deal with high or extreme voice coil displacement and related large signal effects. However, if we consider program materials where sonic fidelity is most needed and meaningful, we notice that middle frequencies are present in substantial magnitudes practically all the time, whereas the deep bass frequencies, that can generate large excursions, are often only occasional (like bass drum strokes) or can be even totally absent (e.g. much of classical music and all human voice). Anyway, in systems with three or more ways the excursion need of the mid-frequency unit(s) is very much relieved by the woofer unit taking care of the low frequencies. Likewise, the use of subwoofers, rather common in today's consumer audio arrangements, remarkably reduces the displacement called for from the other speakers. It is also essential to realize that, due to the nature of auditory masking, a given level of modulation distortion is much more troublesome when the modulating frequency falls in the hundreds of hertz region instead of only tens of hertz, for then the modulation products spread farther away in frequency from the modulated signal tone. For these real-life reasons, it is thus highly necessary and relevant to investigate modulation distortion also in conditions where large displacements do not take place.

The following interference factors can be shown or justifiably expected to confound voice coil current under VC, giving rise to various nonlinear and linear distortions, as diaphragm acceleration is determined by current:

- driver acting as a microphone for sound waves bouncing from cabinet interior walls and passing through the diaphragm,
- driver acting as a microphone for sound waves from adjacent drivers, including coaxial structures,
- mechanical and pneumatic non-idealities of the moving parts causing extraneous EMF effects (e.g. suspension reflections, cone modes); some of these appear as raggedness in the impedance curve,
- *Bl*-variation causing nonlinearity in the motional EMF at low frequencies,
- *Bl*-variation causing fluctuation in impedance's angle and hence phase modulation of current at middle frequencies,

- position-dependent inductance of voice coil causing both amplitude and phase modulation in current,
- current-dependence of voice coil inductance causing strong, mostly odd-order nonlinearity (as observed in this work),
- resistance changes due to temperature variations,
- signal-dependent contact resistance variations in degraded contacts.

A detailed presentation of many of these effects can be found in (MERILÄINEN, 2010, pp. 55–88).

While the position dependence of inductance and its effects are in general relatively widely recognized, the current dependence of inductance has not received due attention. In a tutorial on loudspeaker nonlinearities (KLIPPEL, 2006), it is discussed on the basis of the steel magnetization curve, but then it has been depicted (Table 5 *ibidem*) that the intermodulation distortion due to the effect would vanish when the modulating frequency leaves the bass resonance region (according to the drawing, the distortion would reach a maximum at about $1.5f_s$ and then fade away before $4f_s$ or so). The measurements performed and presented here do not show such a decay, nor did the distortion decline strongly at any frequency of the modulating tone up to the kilohertz region.

Also, the motional EMF and the microphonic feedback action related to it have not been regarded as any source of non-ideality at mid-frequencies when speaker deficiencies are discussed or enumerated. Only the effect on damping nonlinearity has been considered (KLIPPEL, 2006).

3. Measurement setup

All acoustic measurements were performed in room conditions, the drivers carefully fastened in closed enclosures and kept reasonably far from reflective surfaces. The cabinets were filled at least half with effective damping material. The microphone's capsule was at 20 cm distance from the driver's mounting plane.

Another objective of the study was, that the results could be reproduced also by those who don't have access to or cannot afford spending days in an anechoic chamber or don't own a qualified precision microphone. While the absolute levels of distortion may not be very accurate especially at the lowest frequencies due to the nonstandard methods used, the relative differences between VC and CC cases are accurate which is considered to be enough for the purposes of this paper.

The microphone used was of dynamic cardioid type (Sennheiser e815S), and an appropriate response compensation file was used to yield consistent response with a calibrated condenser mic. It was found that the choice of microphone is critical even at the moderate SPL:s it was subject to (about 100 dB). Budget

electret microphones were found useless for this kind of testing due to their inherent distortion. The suitability of any microphone should first be proved with the full test signal by checking that the distortions detected are not inversely related to the measurement distance (as is the case with microphone distortions). The Sennheiser passed this test well and didn't show any signs of contributing to the results presented.

The voltage output amplifier used was built using the power IC LM1875, and the current output amplifier was based on TDA2040 in the current-feedback configuration, with an RC network across the output to ensure loop stability with all loads (Fig. 2).
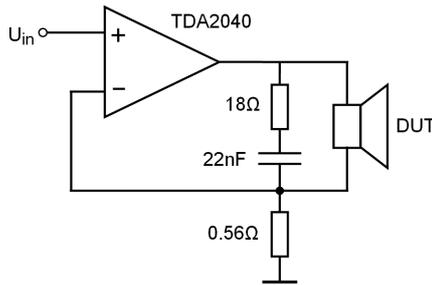

Fig. 2. Power amplifier circuit used for CC.

To ensure that amplifier distortions do not significantly affect the results, both amplifiers were tested with 8 Ω load and with the 300/2500 Hz two-tone signal used in the testing of the woofers. The voltage amplifier exhibited mostly only 2nd harmonic at −75 dB and respective modulation products safely more than 70 dB below the second tone. The current amplifier distortions were of hardly detectable level. The voltage amplifier distortions were also tested at the speaker end of the speaker cable using the examined drivers as the load. The reactive loading caused some observable increase in 3rd-order products, but their levels were still far from the corresponding acoustic distortions. Therefore, it should be clear that the presented VC distortions are not significantly affected by any amplifier or cable-related issues.

The harmonic distortion measurements were performed at a level of 2.83 or 2.0 V, depending on driver impedance. In CC, the signal level was carefully hand-adjusted at each frequency point to match the VC level with better than 0.1 dB accuracy. Matching is imperative here, for a one-decibel rise in signal level can raise the distortion components by several decibels.

The two-tone test signal that was used to excite the V/I conversion anomalies of the cone drivers consisted of a lower-frequency tone (f_1) of 150, 300, or 450 Hz, depending on relevance, and a higher-frequency tone (f_2) of 1250, 2500, or 3750 Hz, respectively, with a voltage level of 1/5 of the lower-frequency tone. Here too, the RMS level of the whole signal was set to 2.83 V or 2.0 V. The signal for the tweeter consisted of 2.2 kHz and 16 kHz tones with a voltage ratio 6:1 and at an

RMS level of 2.0 V. Also with the two-tone signals, the CC signal levels of both frequencies were very carefully matched to the VC levels with a cursor in the spectrum window. The total distortion percentages are calculated with respect to the higher-frequency tone and are simply the square root of the sum of each individual percentage squared (excluding harmonic components).

With the above choices of frequencies and amplitude ratios, the characteristic symptoms of nonlinearities arising from the V/I conversion become well evident, and the modulation products are well separated from the harmonic components. In order to be perceptually as meaningful as possible, the two tones lie far enough from each other for minimal auditory masking by the f_1 tone and close enough that the modulation products are not essentially masked by the f_2 tone, which also yet falls in the usual operation range of the driver (no subjective evaluation performed). It is also natural that f_2 is lower in amplitude than f_1 since the spectrum decays with increasing frequency also in real-life signals, and the ear's sensitivity increases with increasing frequency in the midrange. The author also recommends this kind of stimulus for related experiments.

4. Mid-woofer #1

The first sample presented is a 18-cm 4 Ω mid-woofer (Vifa PL18WO09-04) having quite conventional vented ferrite magnet structure, coated paper cone, and NR rubber surround. Resonance frequency f_s of the system was 54 Hz.

Figure 3 shows the amplitude spectrum plot of the modulation distortion (MD) that occurs in the V/I conversion of the driver, that is, the distortion in voice coil current when the driver is excited by a voltage signal – here 300/2500 Hz. It is seen that the 2500 Hz tone current becomes quite severely distorted in the presence of the 300 Hz tone. The modulation product $f_2 - 2f_1$ (1900 Hz) alone is 2.2% (−33 dB) in magnitude with respect to the original 2500 Hz tone. In addition
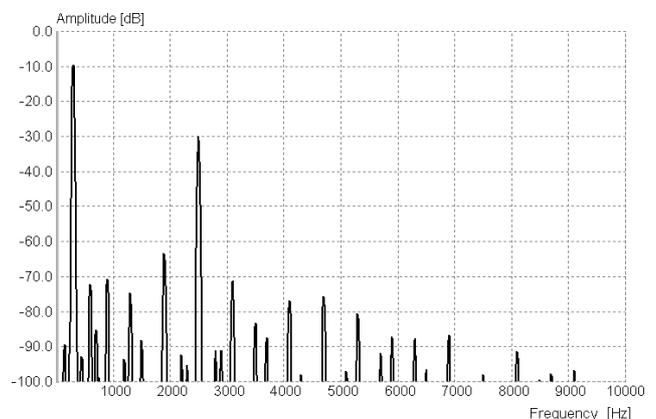

Fig. 3. Modulation distortion of current in mid-woofer #1 under VC at 1 W.

to $f_2 - 4f_1$ (1300 Hz) and $f_2 + 2f_1$ (3100 Hz), the products $2f_2 - f_1$ (4700 Hz) and $2f_2 - 3f_1$ (4100 Hz) are also within 47 dB from the original tone.

The other drivers examined also exhibited very comparable current distortion patterns, e.g. the highest modulation product was always at $f_2 - 2f_1$. Therefore, this kind of measurement is shown only for this driver.

The corresponding acoustic distortion spectrum on VC is seen in Fig. 4. The modulation components coincide very well with the current distortion, indicating that the V/I conversion indeed is the principal source of nonlinearity. The highest of these components are at $f_2 - 2f_1$ and $f_2 + 2f_1$ while the components introduced around $2f_2$ are also rather strong. The total MD of the original 2.5 kHz tone is an alarming 3.1%.
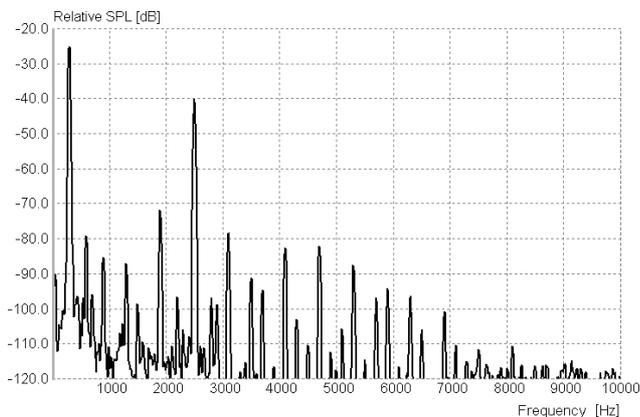

Fig. 4. Mid-woofer #1 modulation distortion:
300/2500 Hz, VC.

The corresponding result on CC is seen in Fig. 5. The six highest modulation products are all reduced by at least 11 dB and the highest one at 1900 Hz even by 16 dB. The respective MD is 0.64% which means an improvement by a factor of 4.8.
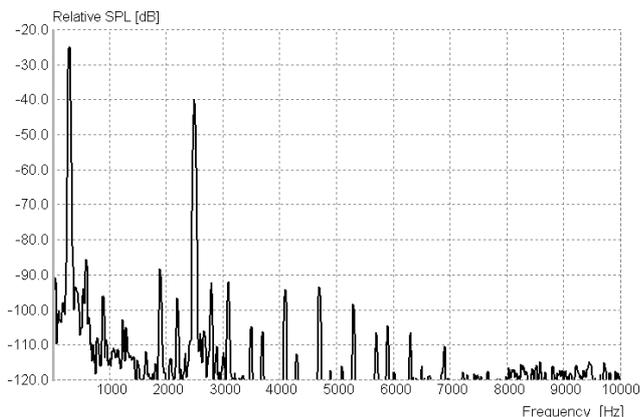

Fig. 5. Mid-woofer #1 modulation distortion:
300/2500 Hz, CC.

The same test was also performed at the halved frequencies, 150/1250 Hz. The corresponding acoustic results on VC and CC are shown in Figs. 6 and 7, respectively. The 2nd-order products nearest to the original 1250 Hz tone ($f_2 \pm f_1$) are caused by various mechanisms (of which the $Bl(x)I$ variation should be the most important) and are often not curable by CC. All the other significant products are instead reduced by more than 12 dB and the one at $f_2 - 2f_1$ (950 Hz) even by 18 dB.
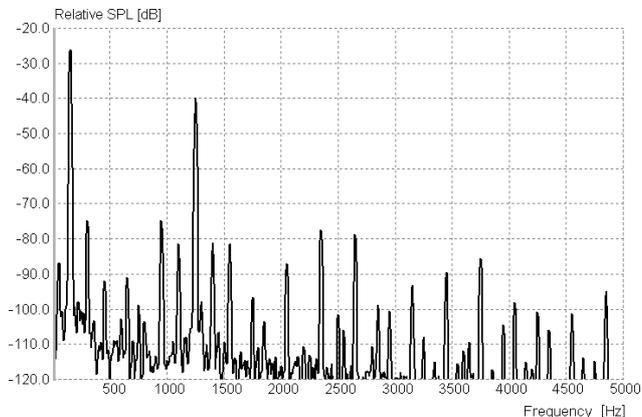
Fig. 6. Mid-woofer #1 modulation distortion:
150/1250 Hz, VC.
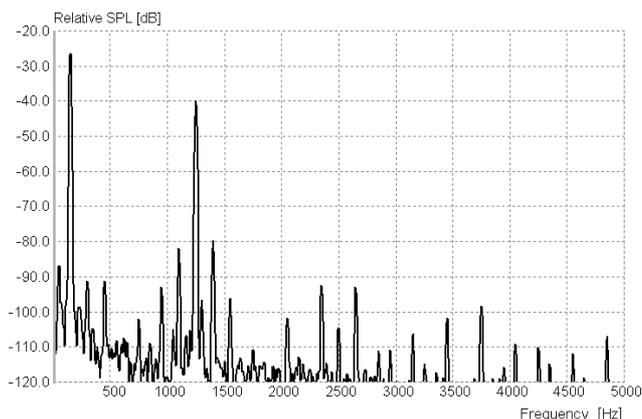
Fig. 7. Mid-woofer #1 modulation distortion:
150/1250 Hz, CC.

The MD (harmonics excluded) is 3.0% on VC and 1.4% on CC; thus, the improvement factor so calculated is 2.1. The real sonic benefit is, however, greater than that since the components not reduced are those closest to the original frequency and are therefore more in its masking shadow than the other components.

All the attenuated MD products are of odd order indicating symmetric nonlinearity effects in the V/I conversion. The obvious cause is the current-dependency of inductance since the displacement-dependency of the same would introduce mostly even-order MD products, that would diminish with increasing f_1. It is also interesting that remarkable sidebands are generated around multiples of f_2 even when there is no signal at these frequencies (the author has no explanation as to the mechanism for this) and that orders even up to 11 ($3f_2 - 8f_1$, Fig. 6) can be observed.

The magnitudes of the most significant MD products have been collected in Table 1.

If the level of the f_2 tone is raised to 1/4 (from 1/5) of the f_1 tone, the components around f_2 usually decrease a little relatively to it, but the components around $2f_2$ tend to increase by a similar amount. The first effect can be understood by considering the waveform of the sum signal: the smaller the amplitude of the f_2 component, the more susceptible it becomes to local variations in the gain factor induced by the f_1 wave.

Figures 8 and 9 show the results on 2nd and 3rd harmonic distortions taken at 2 V level, respectively.

At low mid and high bass frequencies, the 2nd harmonic decreases on CC remarkably. The prominence due to mechanical reasons around 1200 Hz coincides with the driver's surround dip effect (a narrow attenuation in the frequency response usually found in the 1 kHz region, resulting from antiphase vibration of the surround relative to the cone). The overall behaviour of H2 shown in Fig. 8 is quite typical. The main improvement is reaped, however, in the 3rd harmonic that drops at frequencies above 200 Hz on CC by 10–15 dB. Especially in the 1 kHz region the improvement is really crucial.

Table 1. Measured acoustic MD component magnitudes (dB) relative to the higher-frequency (f_2) tone (minus signs omitted). Only components exceeding -55 dB (on VC or CC) are included. The MD percentages also contain some lesser MD components not shown in the Table. Underlines denote better than 20 dB improvement on CC. Values marked with a '~' or '>' are approximations due to the measurement system noise floor.

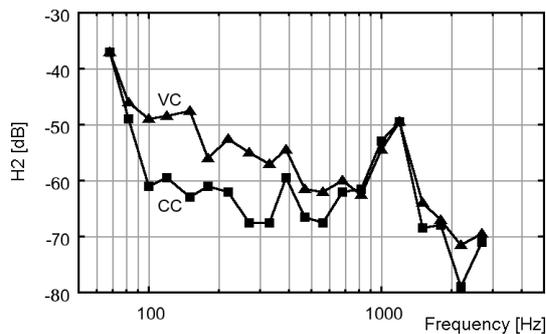|		f_2...						$2f_2$...					$3f_2$...				MD [%]
		$-4f_1$	$-2f_1$	$-f_1$	$+f_1$	$-2f_1$	$+4f_1$	$-5f_1$	$-3f_1$	$-f_1$	$+f_1$	$+3f_1$	$-6f_1$	$-4f_1$	$-2f_1$	$+2f_1$	
Mid-woofer #1																	
150/1250 Hz:	VC	51.0	34.8	41.5	41.1	41.4			47.1	37.6	38.6			53.3	49.6		3.0
	CC	~70	52.9	42.0	39.6	56.2			61.7	52.5	53.0			66.0	61.7		1.4
300/2500 Hz:	VC	47.1	31.8		56.8	38.4	54.7	51.3	42.6	42.2	47.6	54.3					3.1
	CC	65.0	48.3		52.2	52.1	66.3	64.8	54.3	53.4	58.4	64.4					0.64
Mid-woofer #2																	
150/1250 Hz:	VC	49.0	32.6	38.1	41.5	41.0		53.4	47.0	38.2	40.7			53.4	48.1	54.2	3.4
	CC	64.6	49.1	44.5	47.8	53.7		65.8	60.6	52.5	53.8			66.0	61.2	71.0	0.90
300/2500 Hz:	VC	36.2	26.9	44.9	44.0	36.2	49.6	44.5	35.0	39.9	49.0	52.7					5.5
	CC	53.1	43.8	51.7	52.2	50.0	64.4	57.1	47.3	52.1	61.0	64.7					1.0
Mid-woofer #3																	
150/1250 Hz:	VC		40.7	37.5	34.1	50.7				45.3	48.7						2.7
	CC		53.3	37.0	34.6	58.2				73.8	~80						2.4
300/2500 Hz:	VC	51.0	35.1	56.4	48.6	44.4			44.8	40.9	41.0	51.3			53.9	50.8	2.4
	CC	>70	>70	53.6	48.3	~75			~80	~75	~75	~80			>80	~80	0.43
Mid-driver #1																	
150/1250 Hz:	VC	44.0	32.8	49.8	50.2	49.6		47.6	41.8	32.7	32.5	52.7	51.2	52.9	49.7		4.3
	CC	>75	54.6	50.0	45.8	48.8		~80	~80	65.1	67.1	>80	>80	>80	~80		0.73
300/2500 Hz:	VC	45.6	29.7	53.9		41.3		53.2	49.0	53.9							3.5
	CC	~80	66.5	60.0		74.0		>80	>75	>80							0.18
Mid-driver #2																	
450/3750 Hz:	VC	48.5	32.3	40.5	47.0	42.2		54.0	45.5	37.2	38.5	48.4	52.6	48.3	46.4		3.5
	CC	69.4	49.8	44.7	62.6	59.0		70.1	60.5	51.9	52.3	61.4	64.4	61.9	59.4		0.79
FR driver																	
150/1250 Hz:	VC		42.8	44.8	44.0	49.6			53.7	52.2	53.8						1.25
	CC		61.5	46.7	43.9	62.4			>80	>80	>80						0.80
300/2500 Hz:	VC	54.6	45.8		45.1	52.2											0.83
	CC	~80	71.3		43.8	70.8											0.65
Tweeter																	
2.2/16 kHz:	VC		40.6	49.7	53.7												1.0
	CC		59.2	49.0	50.7												0.47

Fig. 8. Mid-woofer #1 2nd harmonic distortion
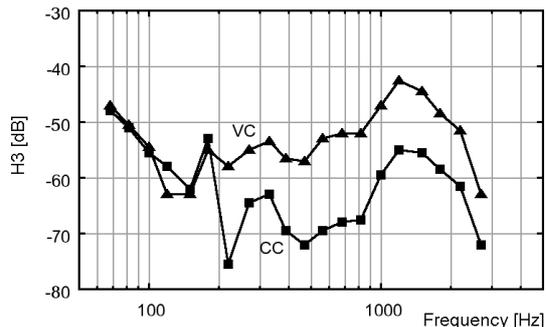vs. fundamental frequency; level 2.0 Vrms.

Fig. 9. Mid-woofer #1 3rd harmonic distortion
vs. fundamental frequency; level 2.0 Vrms.

5. Mid-woofer #2

The second mid-woofer examined is a 6.5-in Peerless Classic 833429 (from ca. 2003) having foam surround, polypropylene cone and large magnet (system $f_s = 62$ Hz).

The most significant acoustic distortion products on VC and CC with the 150/1250 Hz and 300/2500 Hz signals are shown in the second entry of Table 1. On VC at 300/2500 Hz, the worst distortion component is found at $f_2 - 2f_1$ (1900 Hz), while four other modulation products also exceed the 1% level (-40 dB) with respect to the 2.5 kHz tone; resulting in a shocking 5.5% of total MD.

On CC the five highest modulation products are all reduced by at least 12 dB and the highest one even by 17 dB. The total MD is now 1.0% which gives an improvement by a factor of 5.5. Here, the components at $f_2 \pm f_1$ are also reduced, probably due to the absence of the contribution of $L(x)$.

The results with the 150/1250 Hz signal are quite similar to those obtained for mid-woofer #1, except for the $f_2 \pm f_1$, that are now cut by 6 dB on CC, yielding an MD improvement factor of 3.8.

The results on 3rd harmonic distortion are shown in Fig. 10. CC substantially reduces (or more correctly, VC substantially increases) H3 in almost the whole operation area. Very essential is the improvement by about 10 dB throughout the entire midrange, where the VC distortion runs above -50 dB.
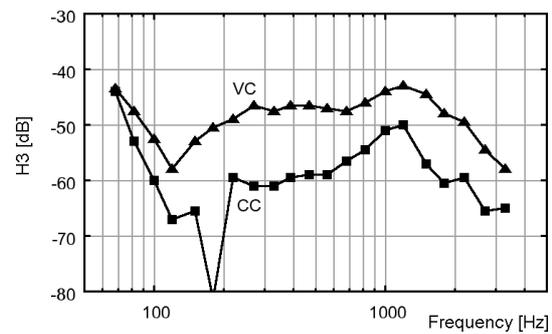
Fig. 10. Mid-woofer #2 3rd harmonic distortion;
level 2.83 Vrms.

In order to gain more insight into the V/I conversion nonlinearity, the harmonic distortion occurring in the current was also measured from this driver, first as such in open air and then after blocking all voice coil movement with epoxy glue. The results are shown in Fig. 11, beginning from 180 Hz, two octaves from the resonance frequency of 45 Hz. (The difference in the current due to the change in impedance between the cases was less than 0.7 dB at 180 Hz.)
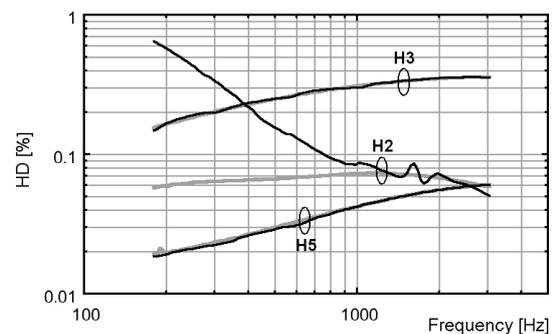
Fig. 11. Mid-woofer #2 current distortion at 2.83 Vrms.
Black: original, free air; gray: blocked.

The odd harmonics, H3 and H5, are very nearly equal in the original and blocked cases, indicating that these components arise from the $L(i)$ nonlinearity (Eq. (4)). The second harmonic, however, behaves very differently in the free and blocked units which can be attributed to the $L(x)$ variation (Eq. (3)), that here dominates H2 below ca. 700 Hz (H4 was lower than H5 and therefore ignored).

It should be noted that the acoustic HD caused by the current distortion is in practice somewhat greater than the latter because the current sensitivity (SPL/current) of any cone speaker increases with frequency due to the cone itself and often also due to the baffle step effect. For example, at 300 Hz, the current H3 equals 0.2% while the acoustic H3 evaluated from Fig. 10 is at least 0.4%, including mechanical and diffraction effects.

The odd-order nature of the observed $L(i)$ nonlinearity doesn't agree well with the common understanding that regards this effect as the result of the

changing permeability when moving about the working point on the $B(H)$ curve (KLIPPEL, 2006) since then we should see mainly asymmetric (2nd-order) distortion. Clearly some further insight is thus needed to explain the observed behaviour, and hysteresis effects (MAZIN, 1999) are likely playing some role. Further, as in a typical motor geometry the current-induced field runs in the proximity of the coil transversely to the permanent field, it is possible that the coil sees the adjacent iron effectively unmagnetized in which case the effective working point for the coil comes closer to the origin of the $B(H)$ characteristic. As the permeability has a minimum at the origin (initial permeability) (LEE, 1955), this could explain the symmetric nature of the $L(i)$ nonlinearity, as well as the rise in inductance with increasing current (MERILÄINEN, 2010, pp. 79–80; PILLONNET et al., 2013, Fig. 9; MERIT, NOVAK, 2015, Fig. 10).

6. Mid-woofer #3

The third sample is a 5-in mid-woofer (Scan-Speak 15W/4434G00) with coated fibreglass cone and an aluminum ring in the magnet circuit (system $f_s = 67$ Hz).

The 300/2500 Hz test results are shown in Figs. 12 and 13, in addition to Table 1. On VC, the highest
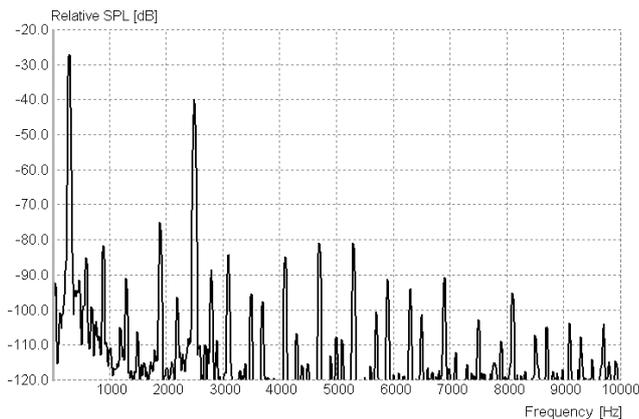
Fig. 12. Mid-woofer #3 modulation distortion: 300/2500 Hz, VC.
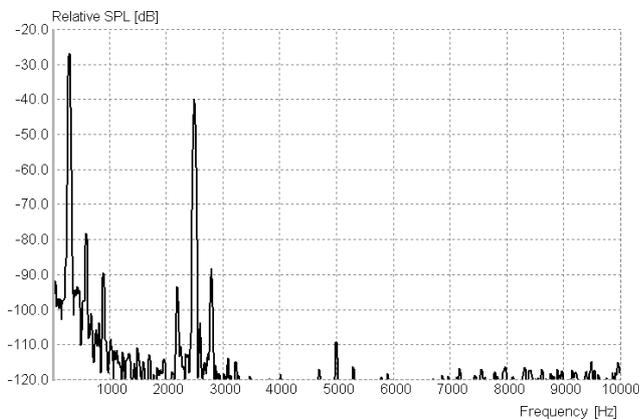
Fig. 13. Mid-woofer #3 modulation distortion: 300/2500 Hz, CC.

modulation peak equals 1.8%, and the total MD is 2.4% with a host of significant peaks. On CC, all modulation products except those at $f_2 \pm f_1$ disappear from sight, the remaining MD being 0.43%.

Also in the 150/1250 Hz test, all significant products except those at $f_2 \pm f_1$ are strongly reduced on CC, though the MD percentage itself does not decrease very much. Here, cone displacement and related MD effects are already quite noticeable.

Figure 14 shows the 3rd harmonic that drops at highest by more than 30 dB and practically vanishes above 400 Hz on CC. Thus, with this driver, the $L(i)$ nonlinearity is by far the dominant source of odd-order distortions in the midrange, despite the shorting ring.
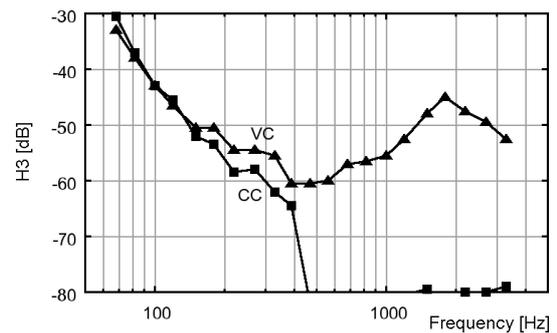

Fig. 14. Mid-woofer #3 3rd harmonic distortion; level 2.0 Vrms.

7. Midrange driver #1

The next sample is a 10-in midrange/high-bass driver (HP-10W) from P Audio, intended for PA use. The cone is made of paper and the surround of plasticized cloth (system $f_s = 82$ Hz).

With the 150/1250 Hz signal on VC, even 3 MD components exceed a 2% level (-34 dB), and there are ten other components above the -55 dB marking threshold used; the total MD being 4.3%. On CC, we are left mostly only with $f_2 \pm f_1$ and $f_2 \pm 2f_1$ that are of a level explainable by the $Bl(x)I$ variation; and there is nothing noticed above 2700 Hz. The respective distortion percentage is 0.73, so the improvement is 5.9-fold. With the 300/2500 Hz signal, the improvement is even more dramatic: 19-fold.
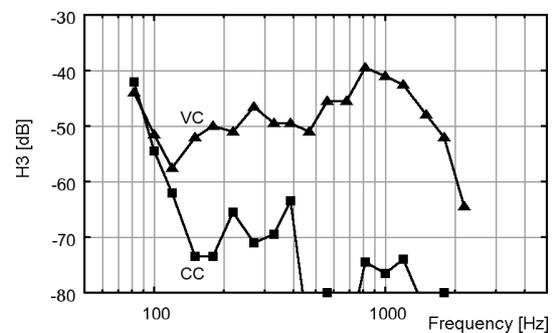

Fig. 15. Midrange driver #1 3rd harmonic distortion; level 2.83 Vrms.

The 3rd harmonic distortion, shown in Fig. 15, is on VC of a clearly harmful level but drops on CC at low mid-frequencies by 15–20 dB and higher up even by 35 dB, falling at times below −80 dB where the limits of the measurement equipment are already encountered. The 5th harmonic of this driver, shown in Fig. 16, tops −60 dB on VC but disappears from sight on CC.
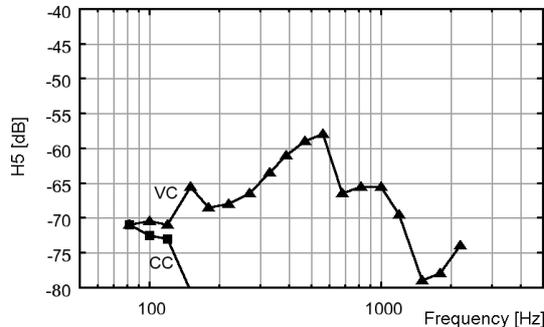

Fig. 16. Midrange driver #1 5th harmonic distortion; level 2.83 Vrms.

8. Midrange driver #2

The second mid-speaker tested is a proprietary 3.5-in cone driver that has been used in Infinity Reference series speakers. The unit has a double ferrite magnet, PP cone, foam surround, and is 6 Ω in impedance (system f_s about 130 Hz).

The MD results are taken at 450/3750 Hz. The most remarkable modulation products on VC are at $f_2 - 2f_1$ (2850 Hz), $2f_2 - f_1$ (7050 Hz), and $2f_2 + f_1$ (7950 Hz), while ten other components are found above −55 dB. The total MD of the original 3.75 kHz tone is 3.5%.

On CC, most of the modulation products are reduced by at least 13 dB and the highest one at 2850 Hz by 17 dB. The respective MD is 0.79%, meaning an improvement by a factor of 4.4. The big asymmetry between $f_2 - f_1$ and $f_2 + f_1$ is an indication of frequency modulation mixing with the amplitude modulation and can be explained by the Doppler effect.

Figure 17 shows the results on 3rd harmonic distortion in the useful range of the driver. H3 drops at
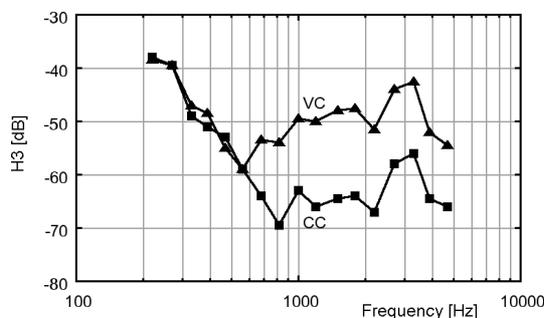

Fig. 17. Midrange driver #2 3rd harmonic distortion; level 2.83 Vrms.

frequencies above 700 Hz by 10–15 dB. The benefit, especially above 1 kHz, in the ear's most sensitive region, is outstanding.

9. A full-range driver

The last cone driver examined is a 8-in paper full-range (Seas FA22RCZ) that features a whizzler cone and a deep drawn copper cap surrounding a prolonged pole piece, making the electrical impedance very flat (13 Ω @ 20 kHz). Voice coil diameter is 26 mm, and system f_s was 82 Hz.

Shorting means of this effectiveness are in practice rare and found mostly only in some full-range transducers. Their effect on distortion is, however, of interest, although with mid-woofer #3 the effect of a mere aluminum ring was not very considerable.

With this sample, all modulation products remain more than 42 dB below the f_2 tone, also on VC, and the peaks around $2f_2$ remain more than 52 dB below. However, CC still eliminates or greatly reduces all other products except those at $f_2 \pm f_1$. The 3rd harmonic, seen in Fig. 18, is also somewhat lower than what is usual, especially above 1 kHz, but CC has still much to clean up.
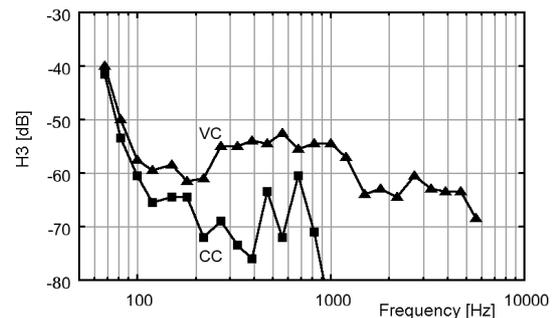

Fig. 18. Full-range driver 3rd harmonic distortion; level 2.83 Vrms.

When comparing with the other drivers, the benefits achievable by the inductance masking measures on the 3rd-order distortions seem to be rather noticeable but limited.

As a less spoken downside of the technique, parts attached to the pole piece also have their own characteristic frequency that makes them prone to metallic ringing.

10. A tweeter

As a representative of HF transducers is taken a 1-in textile dome tweeter (Scan-Speak D2905/950000). The unit has a conventional ferrite magnet structure with ferrofluid and a rear chamber; the resonance frequency being 550 Hz.

The distortion spectrum on VC with a 2.2/16 kHz signal is shown in Fig. 19. The most remarkable modu-
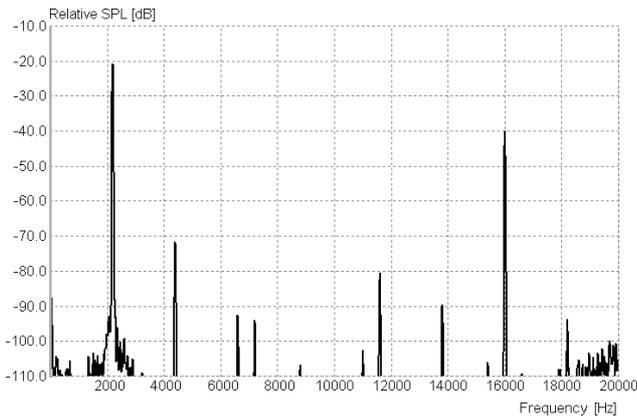
Fig. 19. Tweeter modulation distortion: 2.2/16 kHz, VC.

lation product is also here at f_2-2f_1 (11.6 kHz) and is almost 1% in magnitude relative to the original 16 kHz tone. By including the other products at f_2-f_1 and f_2+f_1, we have a full 1%.

While in general such a number at these frequencies may not yet be deemed too bad, there is an adverse factor: the original tone (16 kHz in this case) may already fall outside the hearing range of the listener, while the biggest distortion component (11.6 kHz) is still well within that range.

The corresponding spectrum on CC is seen in Fig. 20. The most material modulation component (f_2-2f_1) is reduced by more than 18 dB.
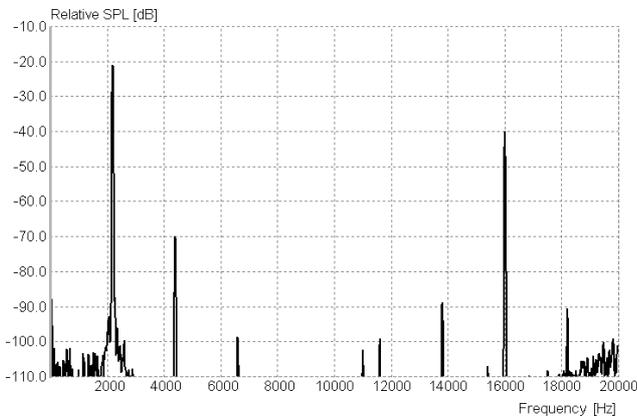

Fig. 20. Tweeter modulation distortion: 2.2/16 kHz, CC.

The lower (2nd-order) products are, however, not reduced; and the one at f_2+f_1 actually rises a little. Thus, in some cases the V/I conversion distortion can be fortuitously working against some other nonlinearity. Despite that, the above percentage is reduced to 0.47.

11. Effect of voice coil formers

When comparing the results above, it is striking how with mid-woofer #3, midrange driver #1, and the full-range driver the reduction in many distortion components is even 30 dB or more on CC, while with the other samples the usual benefit is 10 to 18 dB. The structural difference that can explain this is the conductivity of the voice coil former. In the mentioned drivers, the coil former is made of fibre glass or kapton, whereas all the others employ the more conventional aluminum.

The big difference observed between the types of coil formers suggests that the EMF (eddy) currents in a conductive former make a significant contribution to the distortions of a moving-coil transducer, of course independently of the driving mode. (It is very unlikely that this at least 15 dB average difference in distortion attenuation would arise from the $Bl(x)$ profile and also exactly follow the former material.) On VC, this contribution just seems to be masked under the greater V/I conversion distortions but becomes plainly exposed on CC. Despite the gap regularly used in aluminum formers, there is still a route for the EMF currents via the front portion that is outside the magnetic field; so after all it would be illogical if the EMF-induced currents in the coil former didn't generate distortion in a similar way as they do in the voice coil. Thus, in order to get the full benefit from CC, currents in the voice coil former should also be addressed.

12. Low-frequency considerations

As for low-frequency distortions, it should be noted that there is not a fair way to make these comparisons below the resonance frequency of the driver-enclosure system because a system that is usable in both operation modes is not realizable. This is because, for any given driver, the total Q value will always be higher on CC than on VC; and if the Q is made suitable for VC, it will be excessive for CC, and if made suitable for CC, it will fall short for VC.

The mechanical forces of the harmonic components that fall in the region of the resonance frequency will face a damping force that is about inversely proportional to the effective Q value. Therefore, these harmonic components often show up higher on CC (following quite the difference in frequency response), but increasing the mechanical resistance and lowering the source impedance for the resonance region help. Also, the distortion properties of existing drivers have been optimized for VC. Therefore, we actually don't even know what could be possible to achieve in the other way.

On pure CC, the total Q value equals the mechanical Q value, which should in practice be less than 1 for unpeaking response. Plentiful use of effective damping material, like cotton cloth, can help appreciably to reduce the Q (MERILÄINEN, 2010, pp. 212–214), but the free-air value should also be designed lower than what is now customary. There are mostly two means to

achieve this: by increasing the conductivity of the voice coil former and hence, the damping due to eddy currents or by making the surround material more lossy to increase the mechanical resistance. However, as seen in the foregoing, damping by electrical conductivity in the moving parts is not a choice, as the induced EMF currents effect distortion similarly as the EMF currents in the voice coil, that are just suppressed by CC. Therefore, the usable way to lower the free air Q is to employ more lossy surrounds.

There has been doubt that static electronic compensation of the fundamental resonance would suffice because of drifts in the resonance frequency (SCHNEIDER *et al.*, 2015). However, Spice circuit simulations with measurement-based driver equivalent circuits (similar to those performed in (MERILÄINEN, 2010, pp. 146–149)) by the author have indicated that a series RCL network connected in parallel with the driver can be tuned to be quite tolerable to expectable changes in system f_s, especially when the mechanical Q value is kept moderate by appropriate enclosure filling and choice of the driver. In practice, the Q value of the RCL network needs to be only about 1 irrespective of the speaker's mechanical Q that can be even 4 or so. Also, it is well to note that the tuning of ordinary bass reflex systems is also sensitive to parameter shifts and VC systems additionally to changes in voice coil temperature, so surround materials that harden much with time or with exposure to UV light (MERILÄINEN, 2010, pp. 181–182) should be avoided anyway.

13. Conclusions & discussion

It is shown by measurements with single- and two-tone signals that nonlinear distortions above the fundamental resonance region in moving-coil speakers can be momentously reduced by CC. In an ordinary cone driver, the greatest and most audible modulation products in the midrange and higher typically diminish to a fraction of what they are on VC. Over 30-dB reductions in these products are achieved with drivers having nonconductive coil formers. Usual reduction in the 3rd harmonic in the midrange is over 10 dB with aluminum coil formers and much more with nonconductive ones. The results thus strongly suggest (though do not inarguably prove) that eddy currents in the coil former make a significant contribution to these distortions. The 2nd harmonic also often decreases considerably

on CC. The effect of AC flux reduction techniques is found to be at best much lesser than that of the driving mode.

It is thus evident that the V/I conversion, when left as the job of the transducer, forms the principal source of nonlinear distortions at frequencies where diaphragm movement is not yet large. It is hoped that this, combined with the fact that VC is the standard custom, might give some reason to ponder for those who care about issues of sound quality.

References

1. BORTONI R., FILHO S.N., SILVA H.S. (2007), *Effects of Acoustic Damping on Current-Driven Loudspeakers*, Dissertation presented at the 122nd Convention of the Audio Engineering Society, Vienna.

2. DOBRUCKI A. (2011), *Nonlinear Distortions in Electroacoustic Devices*, Archives of Acoustics, **36**, 2, 437–460.

3. KLIPPEL W. (2006), *Tutorial: Loudspeaker Nonlinearities – Causes, Parameters, Symptoms*, J. Audio Eng. Soc., **54**, 10, 907–939.

4. LEE R. (1955), *Electronic Transformers and Circuits*, 2nd edition, John Wiley & Sons, New York.

5. MAZIN V.Y. (1999), *Modeling of Magnetic Hysteresis and its Influence on Harmonic Distortion in Electrodynamic Loudspeakers*, Dissertation presented at the 106th Convention of the Audio Engineering Society, Munich.

6. MERILÄINEN E. (2010), *Current-Driving of Loudspeakers*, CreateSpace publishing platform, Charleston, ISBN 9781450544009.

7. MERIT B., NOVAK A. (2015), *Magnet-Only Loudspeaker Magnetic Circuits: A Solution for Significantly Lower Current Distortion*, J. Audio Eng. Soc., **63**, 6, 463–473.

8. MILLS P.G.L., HAWKSFORD M.O.J. (1989), *Distortion Reduction in Moving-Coil Loudspeaker Systems Using Current-Drive Technology*, J. Audio Eng. Soc., **37**, 3, 129–148.

9. PILLONNET G., STURTZER E., ROSSIGNOL T., TOURNIER P., LEMARQUAND G. (2013), *Distortion Improvement in the Current Coil of Loudspeakers*, Dissertation presented at the 134th Convention of the Audio Engineering Society, Rome.

10. SCHNEIDER H., AGERKVIST F., KNOTT A., ANDERSEN M.A.E. (2015), *Investigation of Current Driven Loudspeakers*, Dissertation presented at the 138th Convention of the Audio Engineering Society, Warsaw.