Feedback and Distortion in Audio Amplifiers

- invention of feedback
- feedback and nonlinear distortion
- maximum available feedback
- stability
- transient intermodulation distortion
- interface intermodulation distortion

American Telephone and Telegraph Company

Bell System A T & T

1927 :

on the way to becoming by far the largest company in the world

pushing technology to the limit

inventing new technology

> 50% of capital tied up in copper wires

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1963 :

annual turnover $\$10^{11}$ (1963 $$)

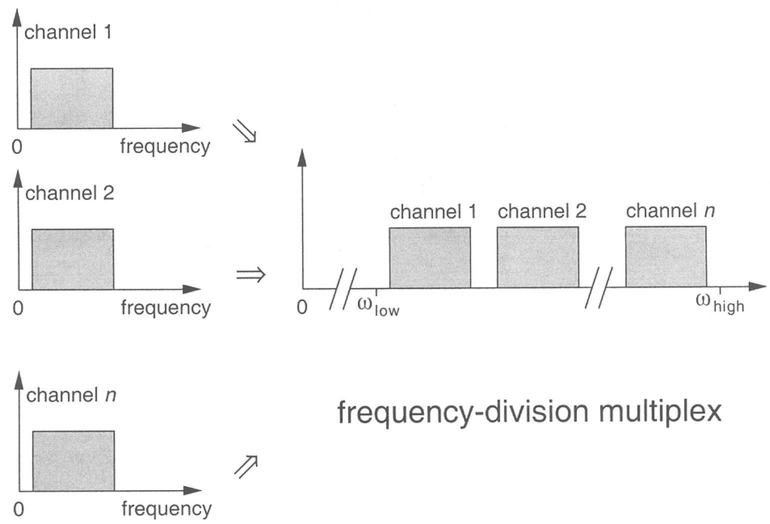
Alexander Graeme Bell $\Rightarrow$ 1 % into research = $\$10^{9}$

Bell Labs :

10^{4} engineers $\$10^{5}$ each to spend

" … dig deep for good solutions "

William Shockley
- hired in 1932 because
  - "… there might be something in those semiconductors …"
- transistor invented 1948



frequency-division multiplex

time-invariant nonlinearity

$$\underset{\text{all } t}{u = } A_0[x + n_2x^2 + n_3x^3 + n_4x^4 + \dots]$$

incremental gain

$$\frac{du}{dx} = A_0[1 + 2n_2x + 3n_3x^2 + 4n_4x^3 + \dots]$$

small-signal gain

$$\left.\frac{du}{dx}\right|_{x=0} = A_0$$

soft nonlinearity

$$u \underset{\substack{\text{soft}\\\text{nonlinearity}}}{\equiv} A_0[x + n_2x^2 + n_3x^3]$$

When an input consisting of two sinusoids

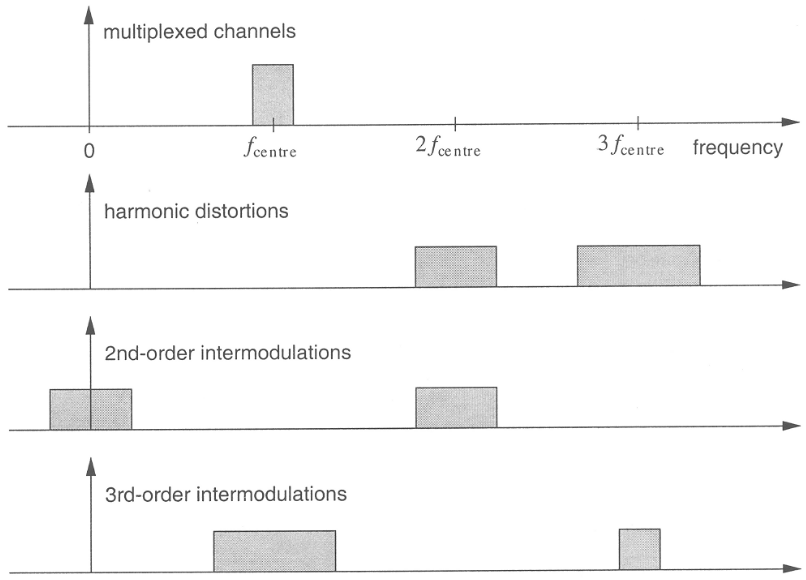
$$x(t) = B_1 \cos \omega_1 t + B_2 \cos \omega_2 t$$

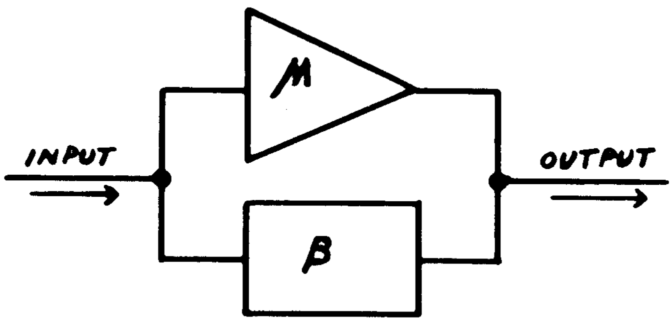
is applied to the unity-small-signal-gain soft nonlinearity

$$u = x + n_2x^2 + n_3x^3$$

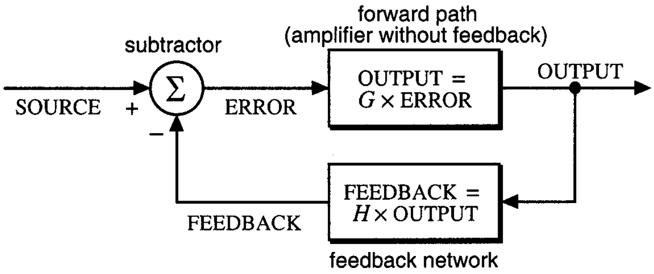
the resulting output is

$u(t) = \frac{1}{2}n_2B_1^2 + \frac{1}{2}n_2B_2^2$	DC shift
$+\left[B_1 + \frac{3}{2}n_3B_1B_2^2 + \frac{3}{4}n_3B_1^3\right]\cos\omega_1 t + \left[B_2 + \frac{3}{2}n_3B_2B_1^2 + \frac{3}{4}n_3B_2^3\right]\cos\omega_2 t$	fundamentals
$+\frac{1}{2}n_2B_1^2\cos 2\omega_1 t + \frac{1}{2}n_2B_2^2\cos 2\omega_2 t$	2nd harmonics
$+\frac{1}{4}n_3B_1^3\cos 3\omega_1 t + \frac{1}{4}n_3B_2^3\cos 3\omega_2 t$	3rd harmonics
$+ n_2B_1B_2\left[\cos(\omega_1 + \omega_2)t + \cos(\omega_1 - \omega_2)t\right]$	2nd-order intermodulations
$+\frac{3}{4}n_3B_1^2B_2\left[\cos(2\omega_1 + \omega_2)t + \cos(2\omega_1 - \omega_2)t\right]$	3rd-order intermodulations
$+\frac{3}{4}n_3B_1B_2^2\left[\cos(2\omega_2 + \omega_1)t + \cos(2\omega_2 - \omega_1)t\right]$	ditto





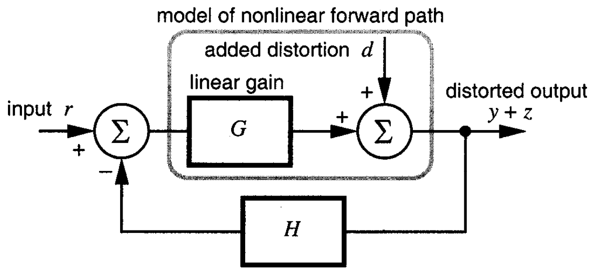
$$\frac{\text{OUTPUT}}{\text{INPUT}} = \frac{\mu}{1-\mu\beta} = \frac{1}{-\beta}\left[1 - \frac{1}{1-\mu\beta}\right]$$



$$A \equiv \frac{\text{OUTPUT}}{\text{SOURCE}} = \frac{G}{1+GH} = \frac{1}{H} \times \left[\frac{1}{1+1/GH}\right]$$

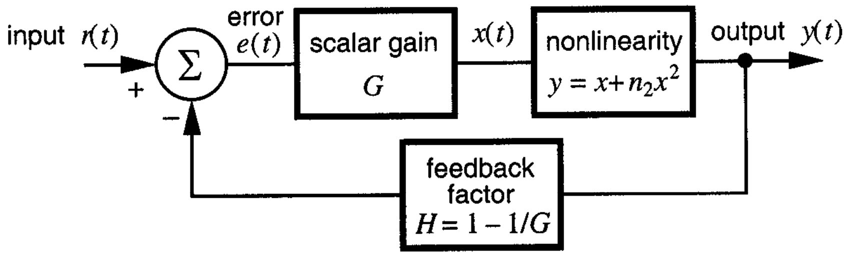
$$= (\text{demanded gain}) \times \left[\frac{1}{1+1/(\text{loop gain})}\right]$$

$$H \equiv \frac{\text{FEEDBACK}}{\text{OUTPUT}}$$

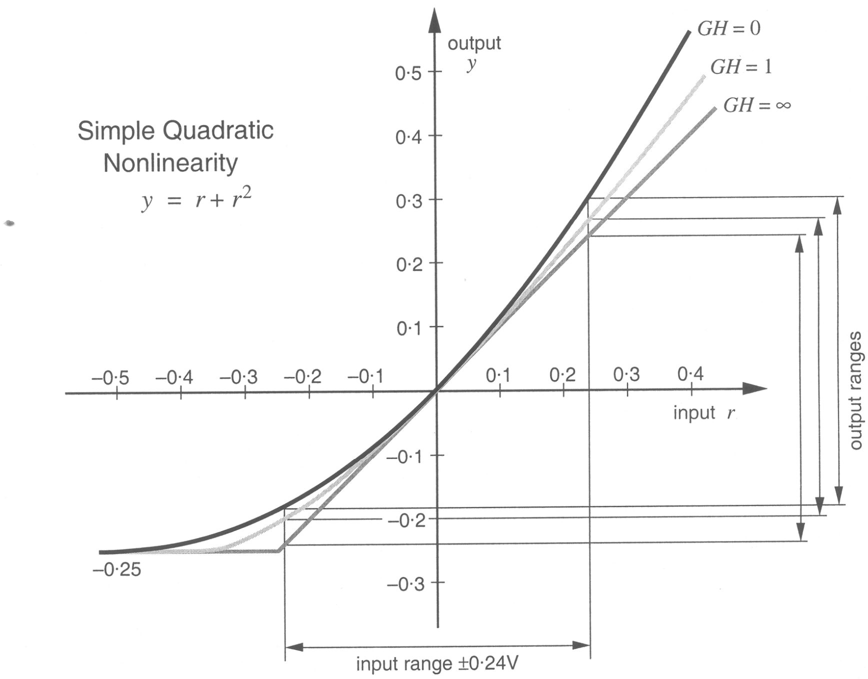


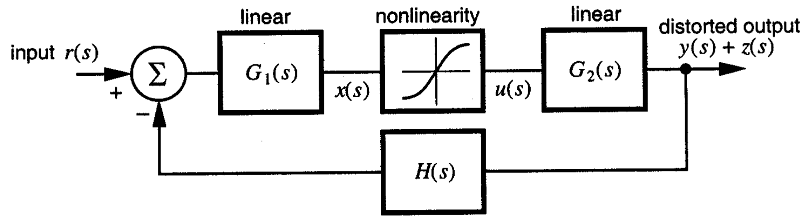
$$(\text{signal at output } y) = (\text{signal at input } r) \times \left[\frac{G}{1+GH}\right]$$

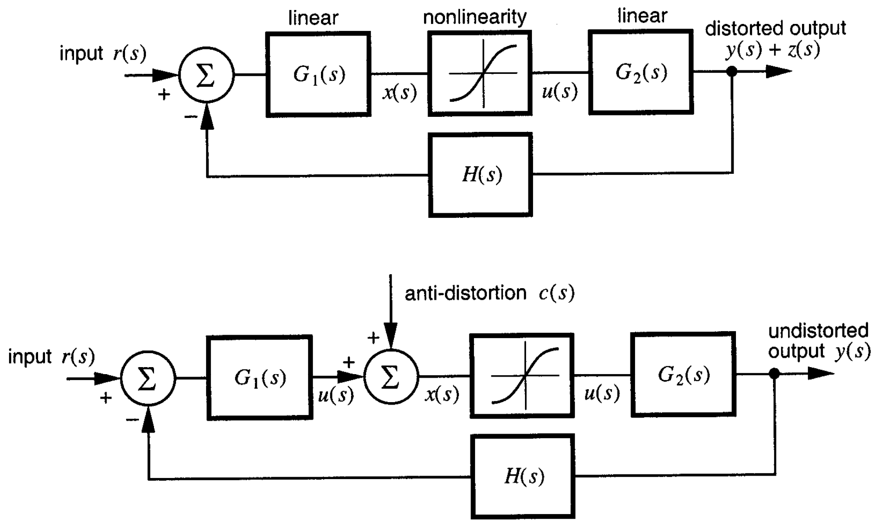
$$(\text{distortion at output } z) = (\text{forward-path distortion } d) \times \left[\frac{1}{1+GH}\right]$$

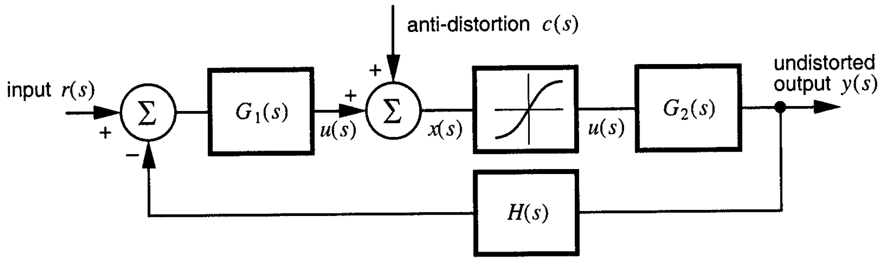


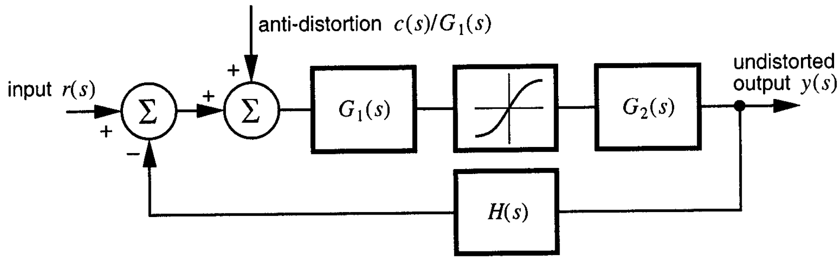
- alter loop gain around a nonlinearity
- keep overall small-signal gain constant

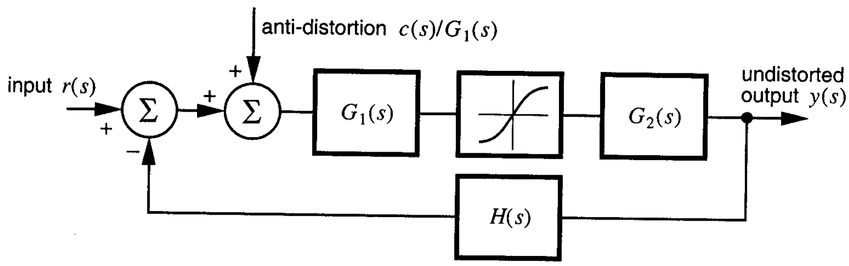


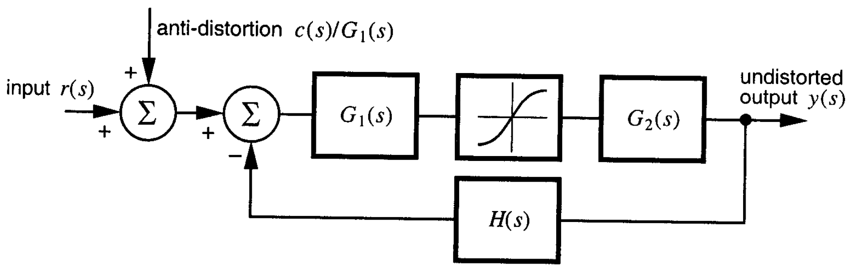

linear
nonlinearity
linear
distorted output
y(s) + z(s)
input r(s)
Σ
G1(s)
x(s)
u(s)
G2(s)
+
−
H(s)

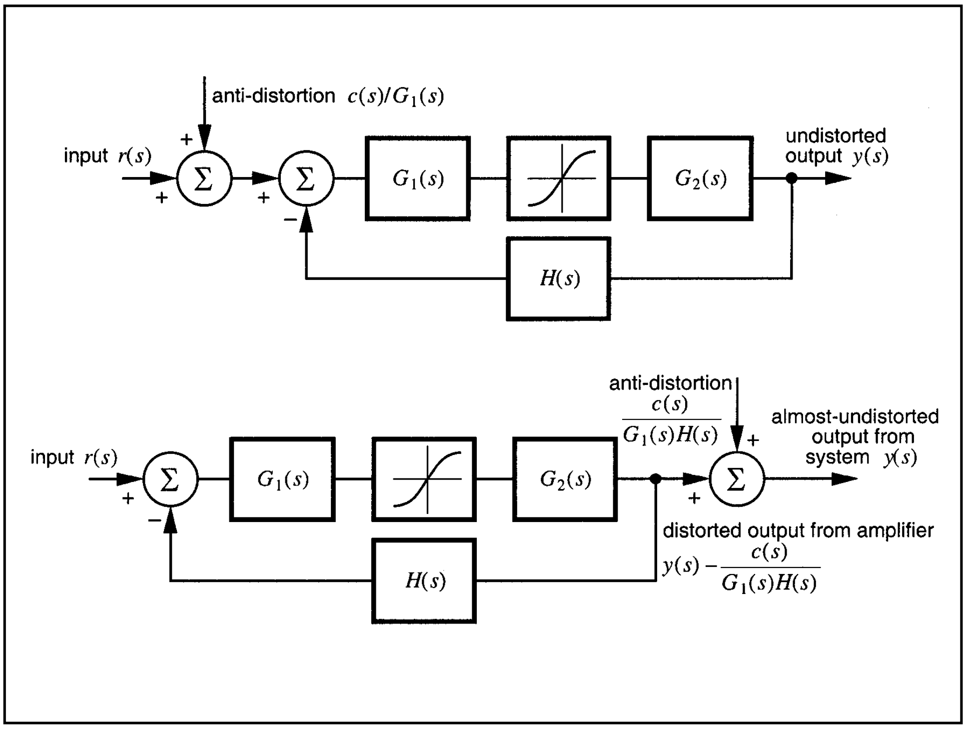

linear
nonlinearity
linear
distorted output
y(s) + z(s)
input r(s)
Σ
G1(s)
x(s)
u(s)
G2(s)
+
−
H(s)
anti-distortion c(s)
undistorted
output y(s)
input r(s)
Σ
G1(s)
u(s)
Σ
x(s)
u(s)
G2(s)
+
−
H(s)

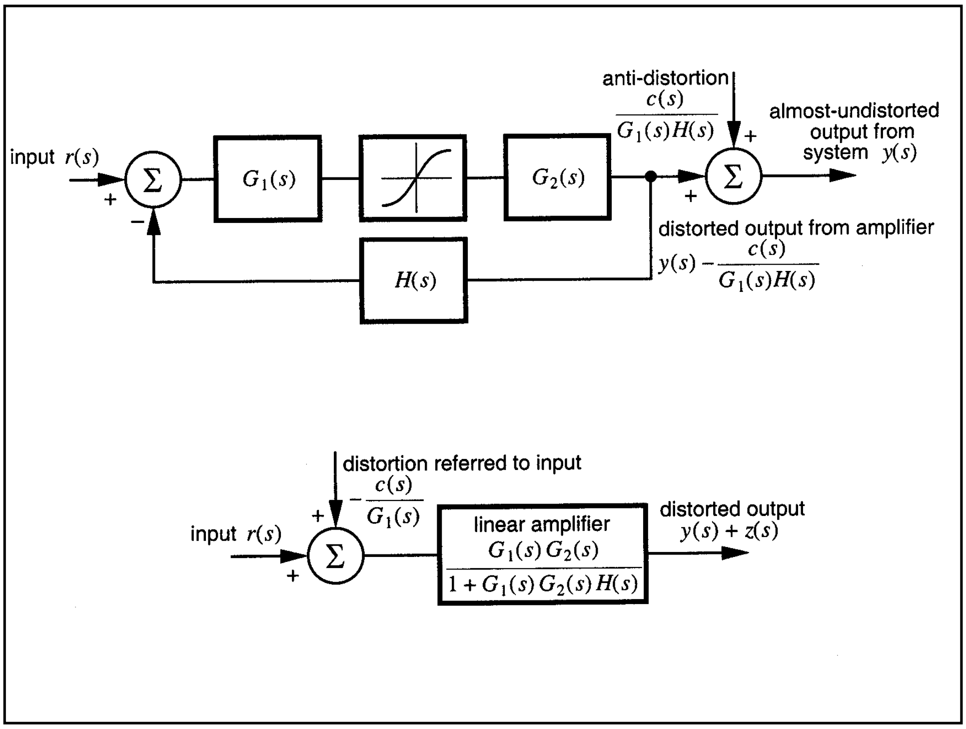

anti-distortion $c(s)$
input $r(s)$
$G_1(s)$
$u(s)$
$x(s)$
$u(s)$
$G_2(s)$
undistorted output $y(s)$
$H(s)$

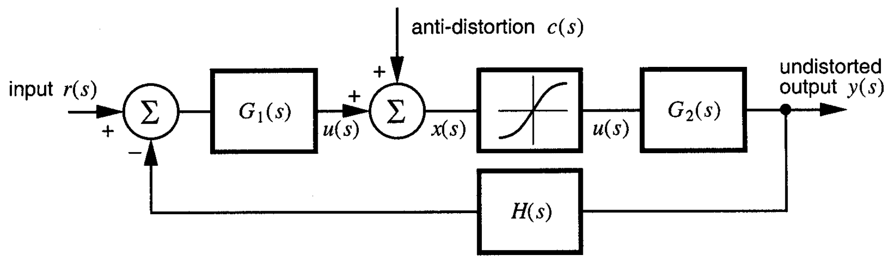

anti-distortion $c(s)/G_1(s)$
input $r(s)$
$G_1(s)$
$G_2(s)$
undistorted output $y(s)$
$H(s)$

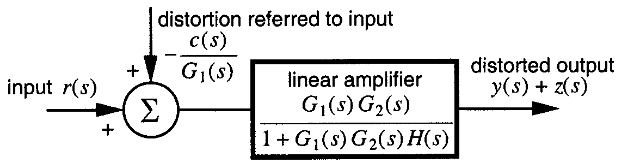

anti-distortion $c(s)/G_1(s)$
input $r(s)$
$G_1(s)$
$G_2(s)$
undistorted output $y(s)$
$H(s)$


anti-distortion $c(s)/G_1(s)$
input $r(s)$
$G_1(s)$
$G_2(s)$
undistorted output $y(s)$
$H(s)$


anti-distortion $c(s)/G_1(s)$
input $r(s)$
$G_1(s)$
$G_2(s)$
undistorted output $y(s)$
$H(s)$
anti-distortion $\frac{c(s)}{G_1(s)H(s)}$
almost-undistorted output from system $y(s)$
input $r(s)$
$G_1(s)$
$G_2(s)$
distorted output from amplifier $y(s) - \frac{c(s)}{G_1(s)H(s)}$
$H(s)$


anti-distortion $\frac{c(s)}{G_1(s)H(s)}$
almost-undistorted output from system $y(s)$
input $r(s)$
$G_1(s)$
$G_2(s)$
distorted output from amplifier $y(s) - \frac{c(s)}{G_1(s)H(s)}$
$H(s)$
distortion referred to input $-\frac{c(s)}{G_1(s)}$
input $r(s)$
linear amplifier $\frac{G_1(s)G_2(s)}{1+G_1(s)G_2(s)H(s)}$
distorted output $y(s)+z(s)$





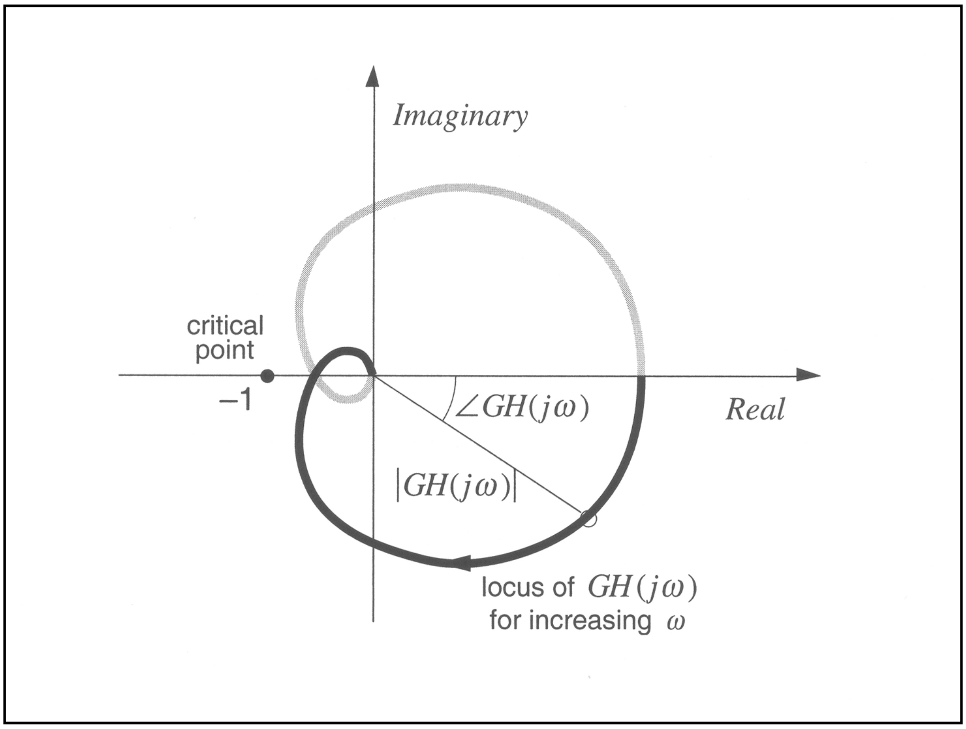
Instability (Oscillation)

$\Rightarrow$ poles of $A(s)$ in RHP

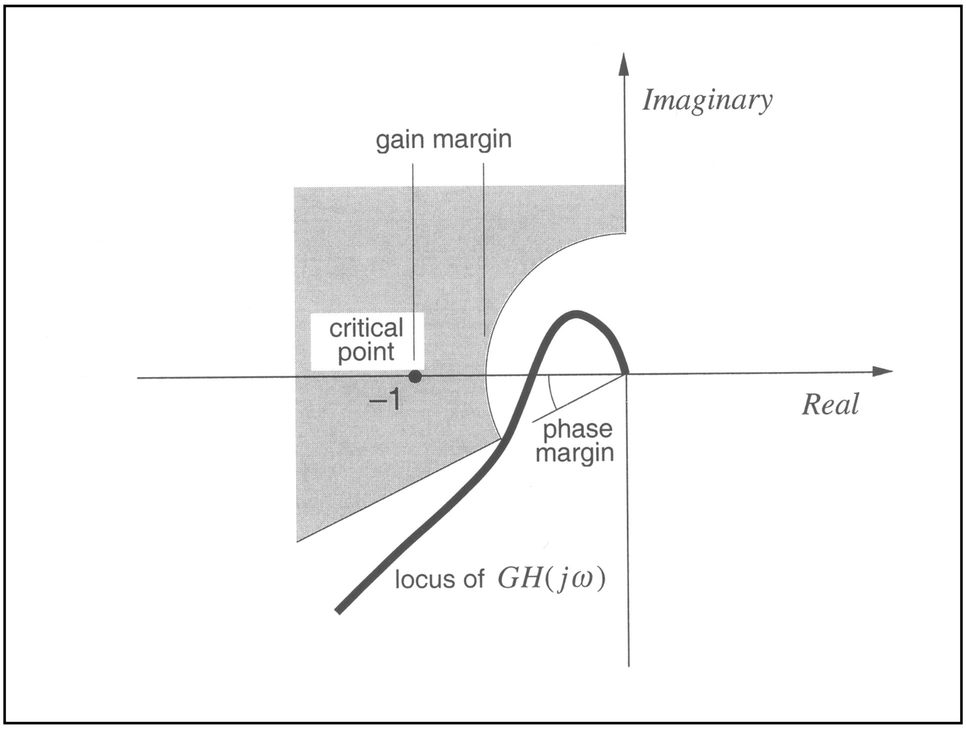
$$A(s) = \frac{G(s)}{1 + G(s)\,H(s)}$$

Nyquist (1932)

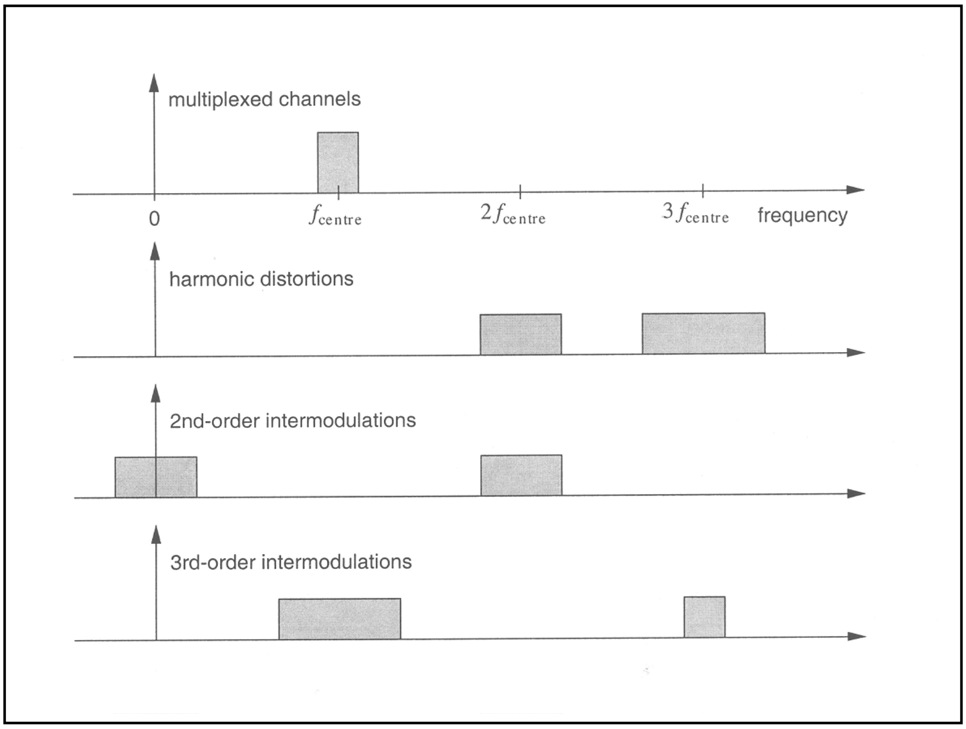
- for a minimum-phase network
  number of poles of $A(s)$ in RHP =
  number of clockwise encirclements of
  critical point (–1, j0) by a polar plot of
  $|GH(j\omega)|$ versus $\angle GH(j\omega)$



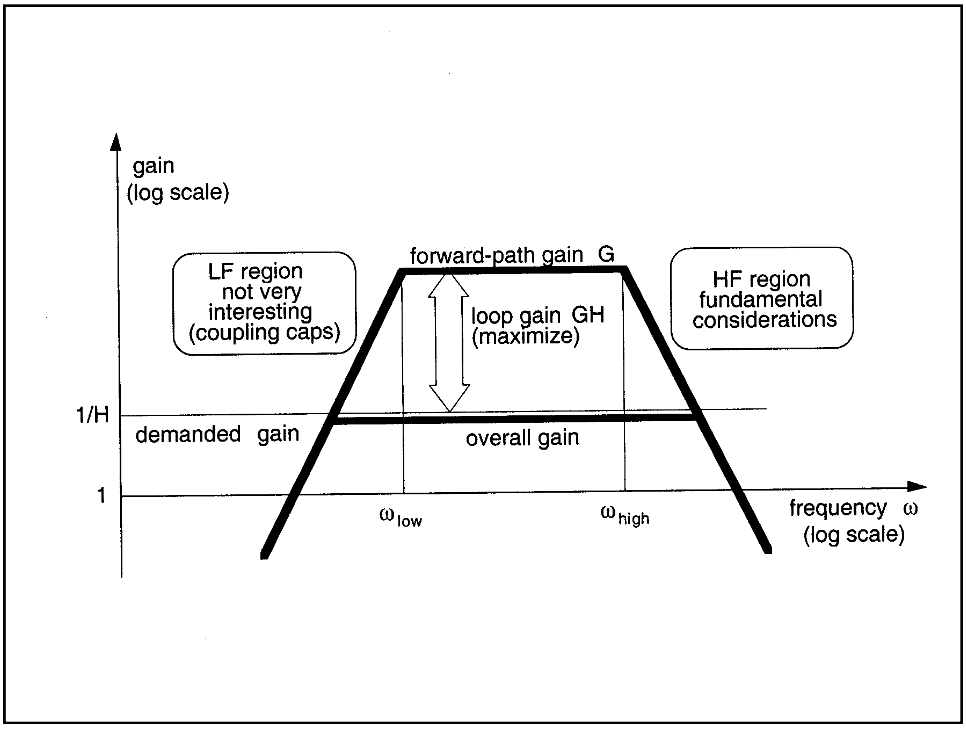
Imaginary
critical
point
−1
$\angle GH(j\omega)$
Real
$|GH(j\omega)|$
locus of $GH(j\omega)$
for increasing ω



Imaginary
gain margin
critical
point
−1
Real
phase
margin
locus of $GH(j\omega)$



multiplexed channels
0
f_{centre}
$2f_{centre}$
$3f_{centre}$
frequency
harmonic distortions
2nd-order intermodulations
3rd-order intermodulations



gain
(log scale)
LF region
not very
interesting
(coupling caps)
forward-path gain G
loop gain GH
(maximize)
HF region
fundamental
considerations
1/H
demanded gain
overall gain
1
ω_{low}
ω_{high}
frequency ω
(log scale)

Bode's famous relation between gain and phase shift

integral over all frequencies 0 to ∞

w is a "dummy" variable of integration

$$\angle K(j\omega) = \frac{1}{\pi}\int_0^\infty \left[\frac{d\ln|K(jw)|}{d\ln(w/\omega)}\right]\left[\ln\left|\frac{w+\omega}{w-\omega}\right|\right]\frac{dw}{w}$$

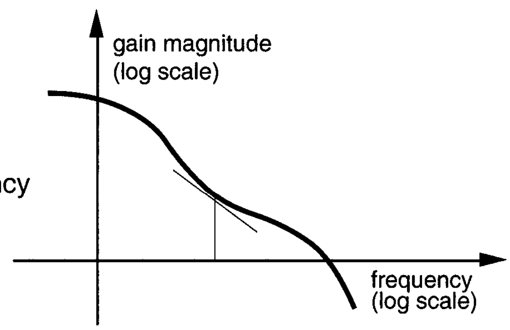
phase shift at any frequency ω

weighting factor

goes to infinity at frequency ω of interest

gradient of a plot of |gain| versus frequency
on logarithmic scales
(Bode plot)

Phase shift at any frequency
is dominated by gradient of
gain magnitude at the frequency
(both on log scales)



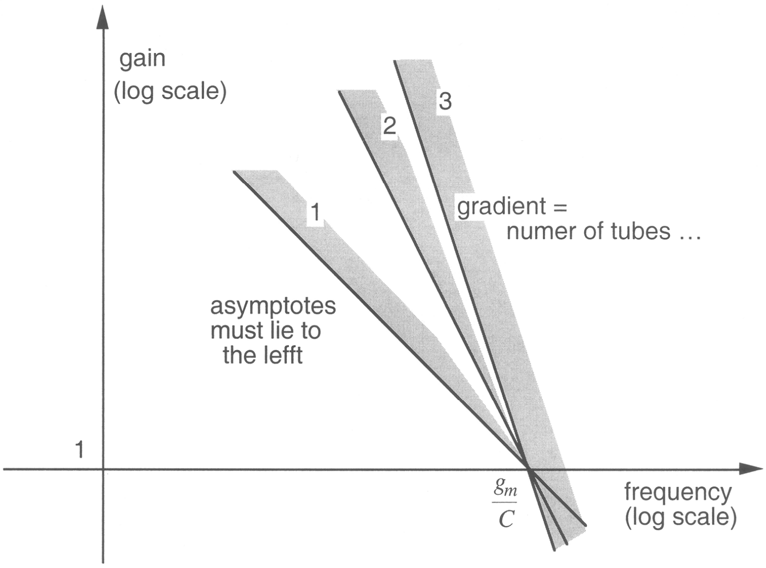
gradient	plain English	jargon	phase
gradient = –1	inverse proportion	–20dB / decade	– 90°
gradient = –2	inverse-square law	–40dB / decade	–180°
gradient = –3	inverse-cube law	–60dB / decade	– 270°
gradient = – n	gain ∝ (frequency)$^{-n}$	–20 n dB / decade	– 90° × n

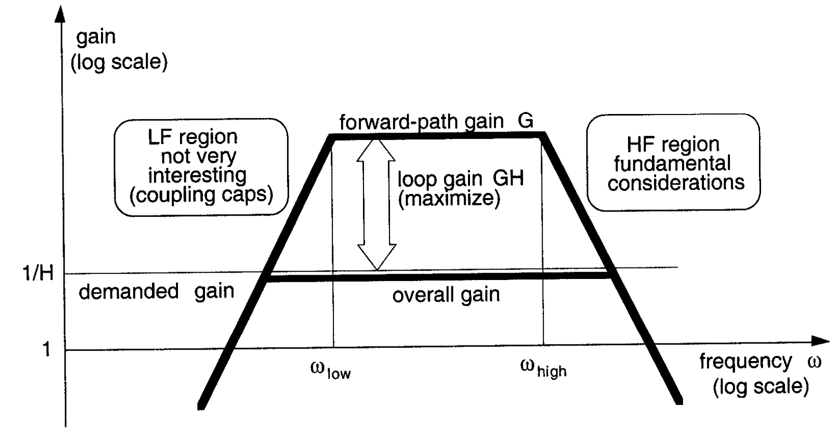
Llewellyn and Peterson (1941)

$$\frac{g_m}{C} \leq \frac{\text{fiddle factor}}{\text{electron transit time}}$$

transit time

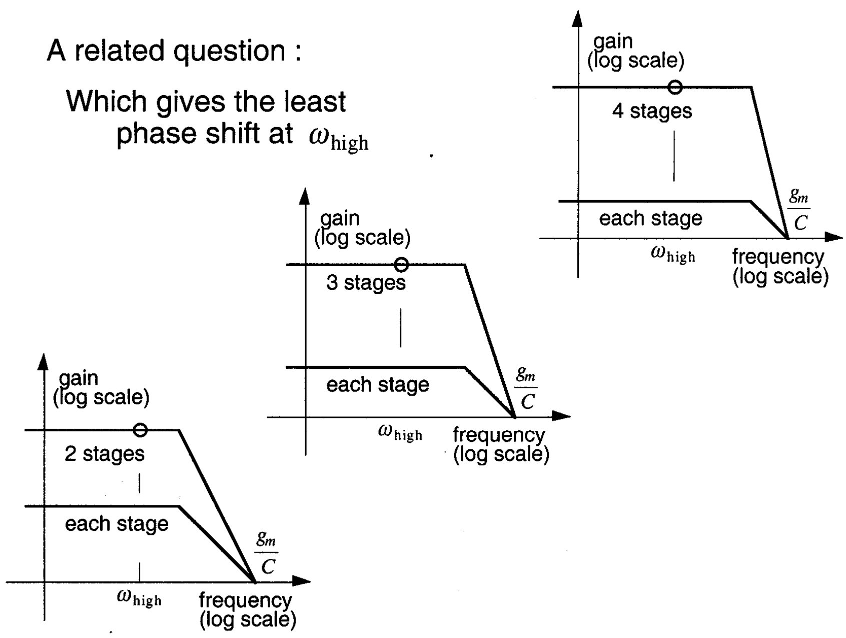
- vacuum tubes $\Rightarrow$ grid-cathode spacing
- BJTs $\Rightarrow$ base width
- FETs $\Rightarrow$ channel length

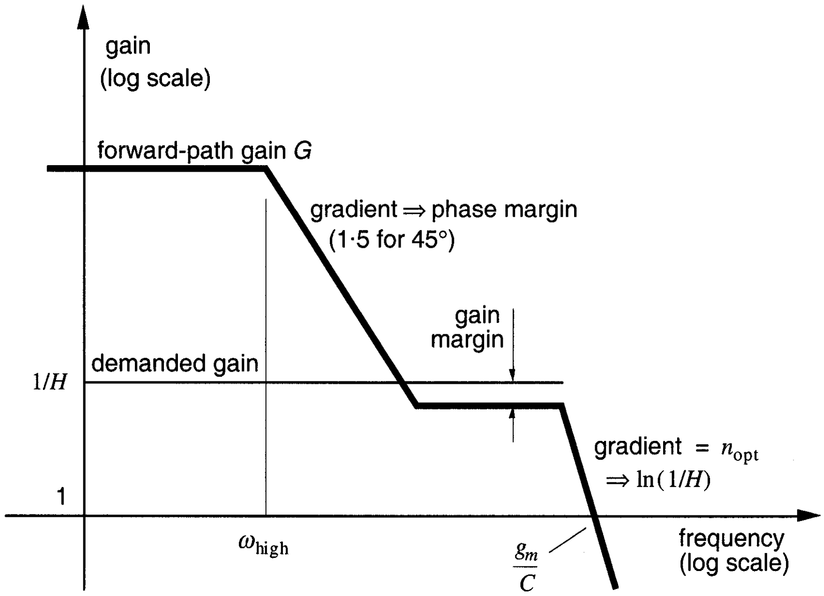




A related question :

Which gives the least phase shift at ω_{high}

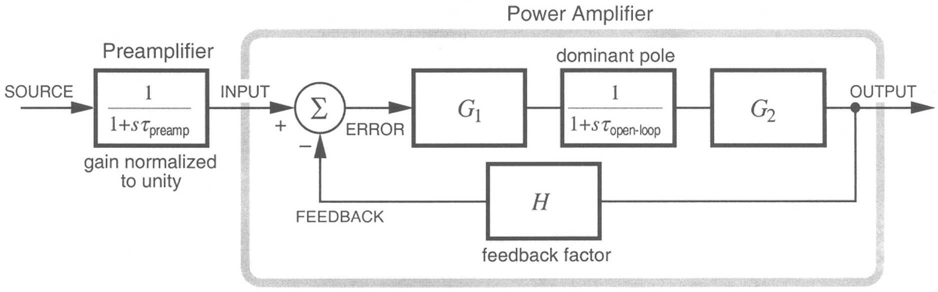




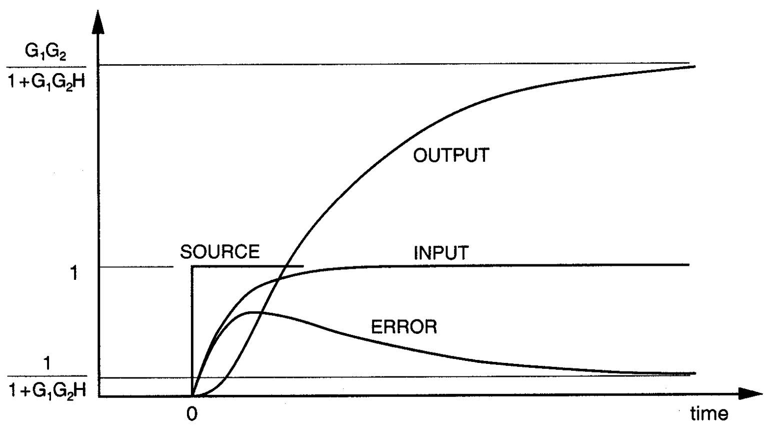
Transient Distortion in
Transistorized Audio Power Amplifiers

M Otala

IEEE Transactions on Audio and Electracoustics
Volume AU-18, Number 3, September 1970
pages 234—239

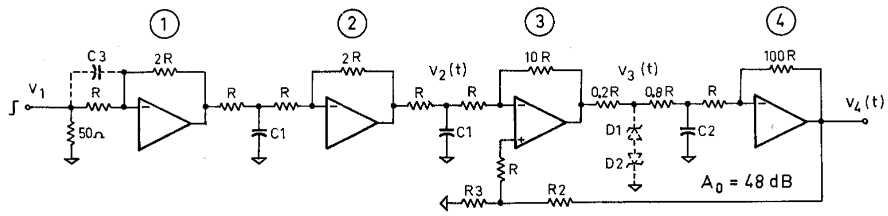


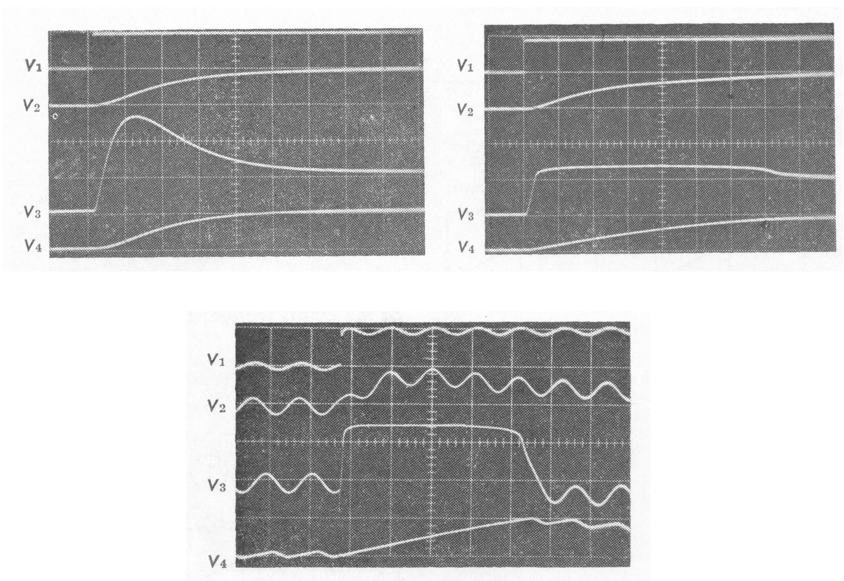
Otala's model for transient intermodulation distortion
(TIM or TIMD)



The ERROR signal :

initial rise	peak amplitude	final decay	final amplitude
$\approx \exp\left(-\tau_{\text{preamp}}\right)$	$\approx \dfrac{\tau_{\text{open-loop}}}{G_1 G_1 H \tau_{\text{preamp}}}$	$\approx \exp\left(-\dfrac{\tau_{\text{open-loop}}}{G_1 G_2 H}\right)$	$\approx \dfrac{1}{G_1 G_2 H}$


1
2
3
4
V1
C3
2R
R
50Ω
C1
v2(t)
10R
v3(t)
0,2R
0,8R
D1
D2
C2
100R
v4(t)
R3
R2
A0 = 48 dB


V1
V2
V3
V4

Otala's Conclusions
(EMC's paraphrase)

TIM occurs if the open-loop response of the power amplifier is slower than the response of the preamplifier

There is an optimum amount of feedback
- Too much — increases TIM
- Too little — increases 'ordinary' distortion

Lag compensation techniques are inadvisable
- Increase TIM

Co-Workers at Monash

Greg Cambrell

Kishor Dabke

Other Critiques …

T. Jelsing (1976)

M. Rigby (1977)

B. Olsson (1977)

Bob Cordell (1978) — Bell Labs

Peter Garde (1978) — Sydney

Jung, Stephens & Todd (1979)

Dick Small (pre-1980) — Sydney

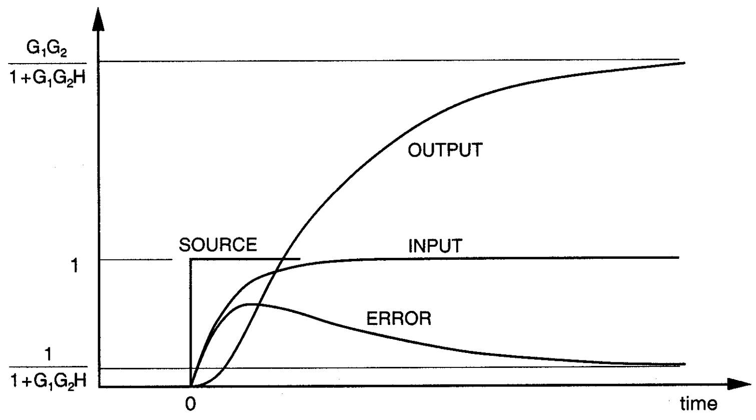
Errors

Normalization …

Confusion between overshoot and overdrive

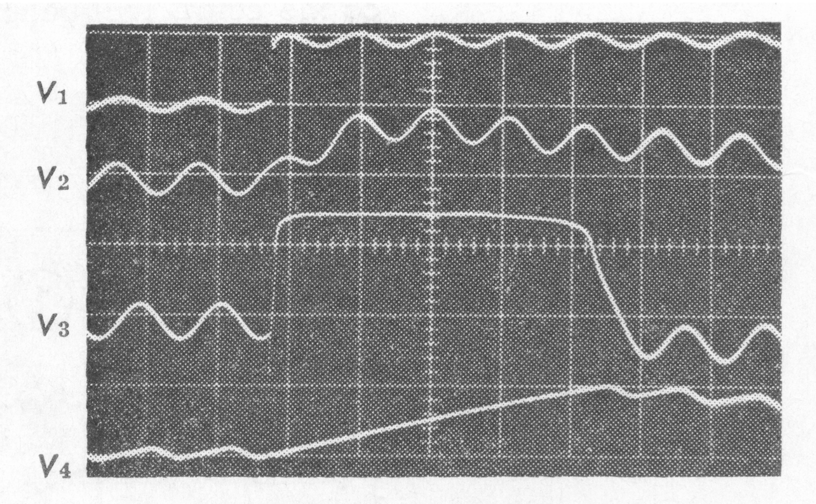
- Peak ERROR remains constant as GH increased, subject …
- Final ERROR becomes smaller as GH increases

Invalid model …



The ERROR signal :

initial rise	peak amplitude	final decay	final amplitude
$\approx \exp(-\tau_{\text{preamp}})$	$\approx \frac{\tau_{\text{open-loop}}}{G_1 G_1 H \tau_{\text{preamp}}}$	$\approx \exp\left(-\frac{\tau_{\text{open-loop}}}{G_1 G_2 H}\right)$	$\approx \frac{1}{G_1 G_2 H}$



Errors

Normalization …

Confusion between overshoot and overdrive

- Peak ERROR remains constant as GH increased, subject …
- Final ERROR becomes smaller as GH increases

Invalid model …

Over-testing

"flute" $\Rightarrow$ 600 kHz
"bass drum" $\Rightarrow$ 200 nS rise time
$\Rightarrow$ 1·6 MHz cut-off

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Summary

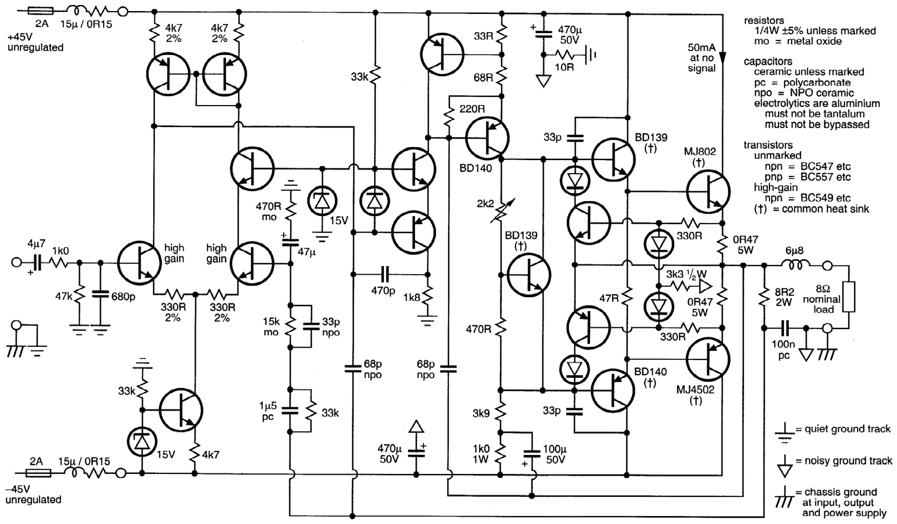
- Wrongly classified

  "Transient distortion" not used in accepted sense
  Valley & Wallman: *Vacuum-Tube Amplifiers* (1948)

- Not a new phenomenon

  Well-known in 1970 as "slewing"
  Early analyses by A.B. Thomas in 1946
  and J.E. Flood in 1953
  Definitive analysis (in context of op amps)
  by Solomon, Davis & Lee in 1969

- Not restricted to transients (also sine waves)
- Not restricted to "transistiorized" circuits
- Not restricted to audio amplifiers



60-watt 8-Ω NDFL Amplifier (revised protection)

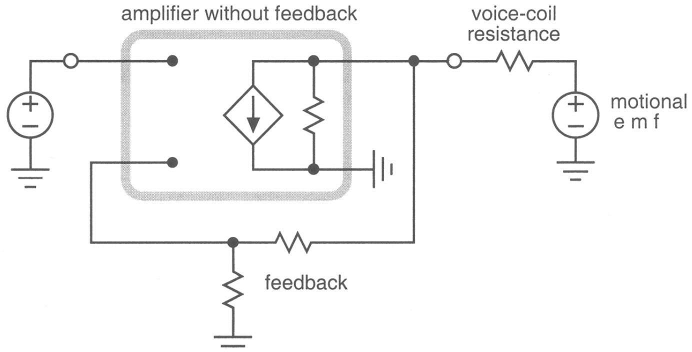
Intermodulation Distortion at the Amplifier-Loudspeaker Interface

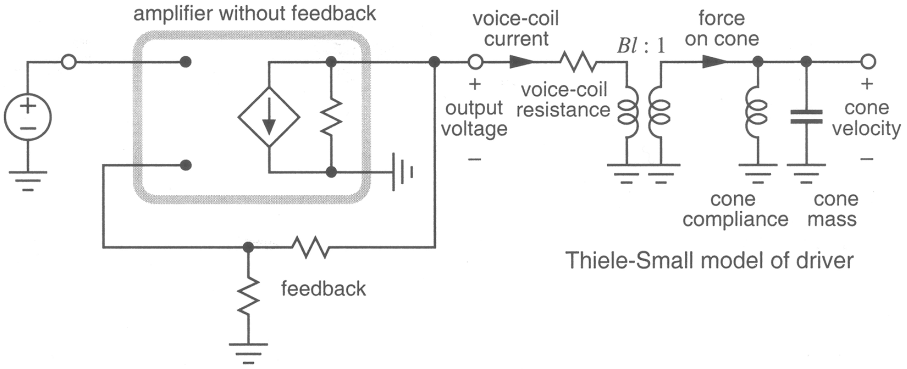
M Otala

AES Convention pre-print

Wireless World

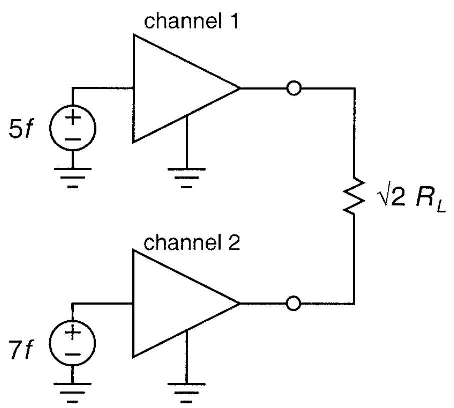
- loudspeaker (“driver”) is an electro-mechanical system
- cone moves as a consequence of
  - driving current
  - inertia (e.g., following a step input)
  - incident sound (room or enclosure reflections)
- voltage induced in voice coil by motion
- in a feedback amplifier this voltage is returned to input
- possibility of intermodulation
- more feedbck $\Rightarrow$ greater intermodulation
- especially for high-output-resistance amplifiers
  - pentodes or CE-BJTs

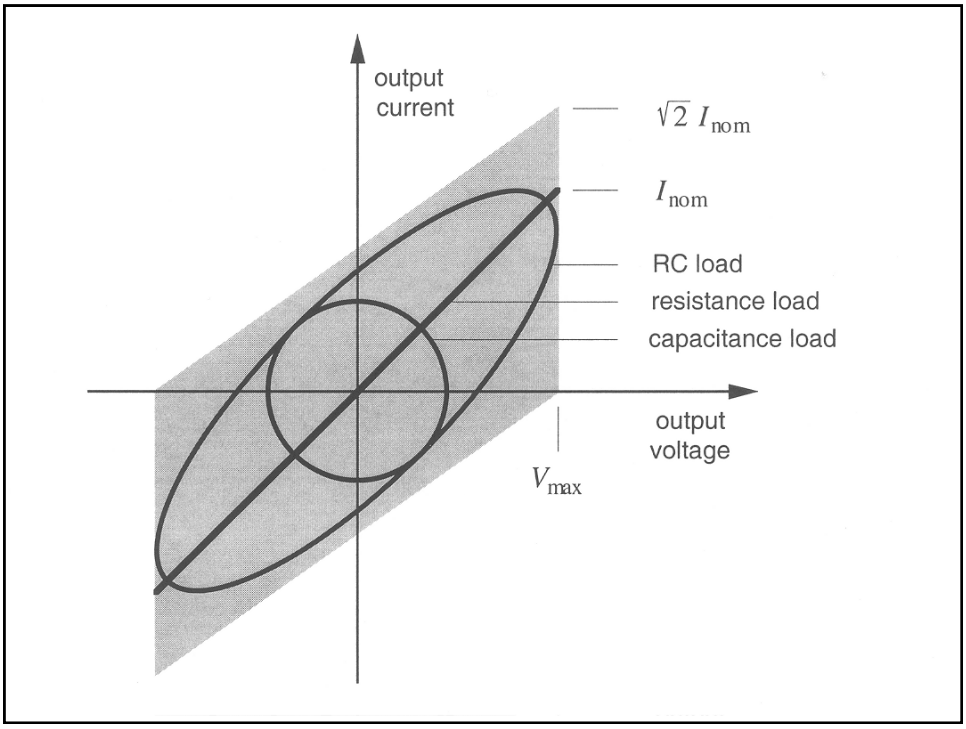


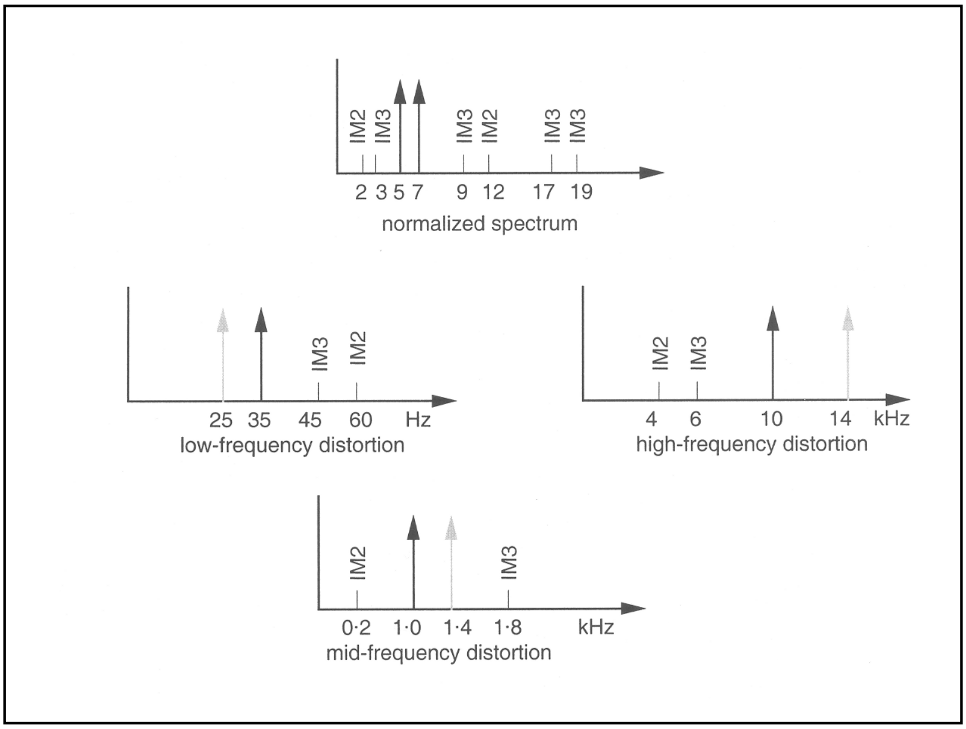


Input-Output Intermodulation Distortion

(with Greg Cambrell)




output
current
$\sqrt{2}\, I_{nom}$
I_{nom}
RC load
resistance load
capacitance load
output
voltage
V_{max}


IM2
IM3
IM3
IM2
IM3
IM3
2 3 5 7 9 12 17 19
normalized spectrum
IM3
IM2
25 35 45 60 Hz
low-frequency distortion
IM2
IM3
4 6 10 14 kHz
high-frequency distortion
IM2
IM3
0·2 1·0 1·4 1·8 kHz
mid-frequency distortion