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The Many Faces of Distortion[1]

A look at the various types of distortion and the results of an interesting experiment involving counter-Electro-Magnetic force (EMF).

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(Translated by Jan Didden[2])

Distortion in audio, defined as a lack of fidelity with respect to a reference, applies to an amplifier when the output signal the amplifier delivers is not exactly the same as the signal applied to the input. Even if it is possible to classify it in different categories, distortion remains difficult to recognize "in the field," in the presence of a music signal.

Since the birth of the first amplifier circuits for low-frequency applications, designers have searched to battle all forms of distortion which lead to a deformation of the signal to be reproduced. Basically, distortion can be subdivided into many dozens of categories, one of which is the type known as "nonlinear," or "amplitude distortion." This, in turn, exists in different forms: amplitude-frequency nonlinearity, harmonic distortion, intermodulation distortion (which is produced when the amplifier is presented with two or more signals simultaneously), transient distortion, phase distortion, frequency distortion (where the amplification factor is not constant over frequency), and scaling distortion (which arises when the amplification factor varies with signal amplitude).

In the case of the power amplifier, these various types of distortion intertwine themselves with those produced by the loudspeaker driver and the speaker acoustic enclosure, and their association can give rise to other amplifier stability problems or even re-inject into the amplifier as a "Counter-Electro Magnetic Force" (CEMF) signal sent back by the loudspeaker. We will look at it later.

STEADY-STATE AND TRANSIENT HARMONIC DISTORTION

We speak of harmonic distortion if an amplifier generates—as a result of a signal to be amplified, for example a 1kHz sine—one or more harmonics of even or odd order of a certain level: 2kHz, 3kHz, 4kHz, 5kHz, 10kHz. This form of distortion will more or less strongly alter the original signal and its harmonic envelope and will produce timbre changes that have been the subject of attempts to evaluate, quantify, and classify since the beginning of electroacoustics.

To speak about harmonic distortion is also to speak about harmonic sounds and dissonances, much of the basics that have given music its famous chromatic range made up from the 12 notes in the tempered range. Our sensitivity to consonant and dissonant sounds merits some explanation. In the case of light and vision, the mix

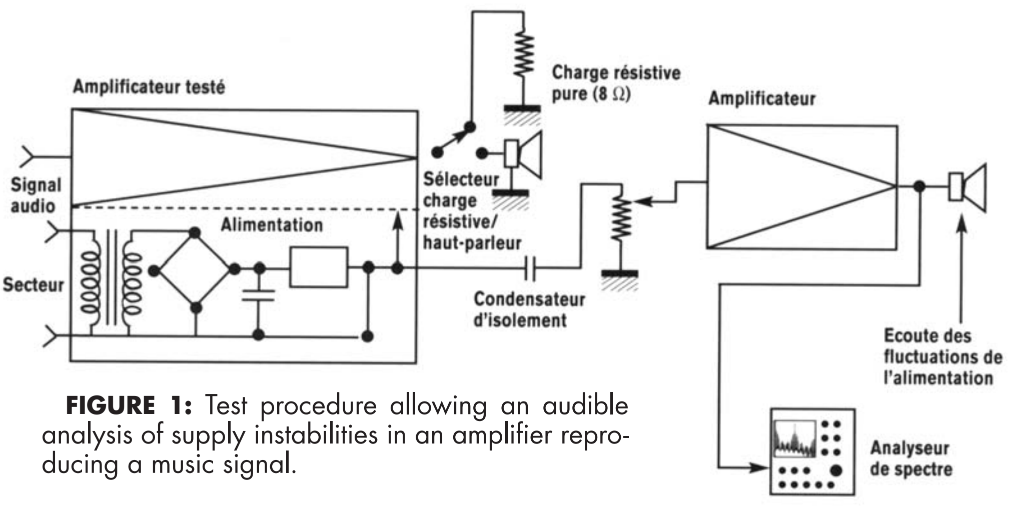

FIGURE 1: Test procedure allowing an audible analysis of supply instabilities in an amplifier reproducing a music signal.

of blue and yellow produces a kind of harmonic result—green—which, in isolation, no longer allows you to discern the original components, yellow and blue.

Our perceptive system for sound functions quite differently. If you play two notes simultaneously on a piano—a "do" and a "sol"—you hear the two tones as a harmonic fusion while still being able to discern the two. The color "white" can be considered as such a perfect harmonic mixture of the seven colors of the rainbow that our eyes are unable to discern the components. Even if this example is applicable for light and vision, it is not at all the same in the case of sound.

White noise—a very complex sound that you could transpose into white light—is not audibly perceived as a perfect fusion of myriad pure tones. It is actually perceived as a great number of tones, a diversity of sounds giving the impression of being badly mixed.

This extraordinary capacity of the ear to analyze a sound as complex as white noise proves the fact that these tones—however close or numerous they are—are not sufficient to fuse into a single and unique sound, and impossible to generate so that you could baptize it "white sound." It is the German Georg S. Ohm (1789–1854), a physicist, to whom we owe the fundamental laws of electrical current and also the contribution of this fundamental faculty of the ear known as "Ohm's law of acoustics."

HARMONIC SOUNDS, DISSONANT SOUNDS

The study of harmonic sounds and dissonant sounds goes back many centuries. Interested readers should avail themselves of the works of Zarlin (Italy,

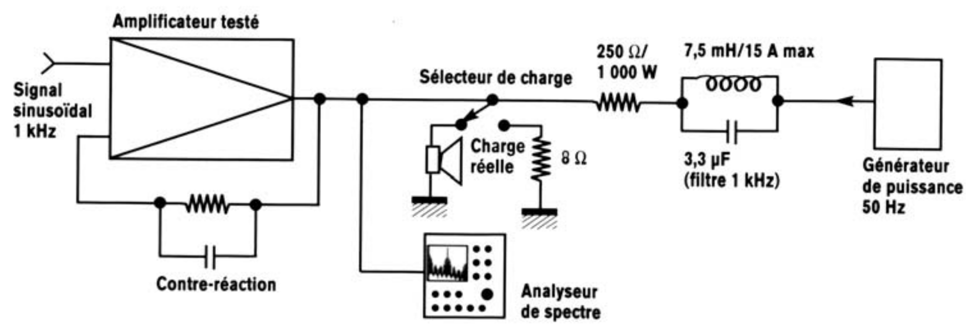

FIGURE 2: Interface Inter-Modulation distortion test under load conditions, designed to simulate the occurrence of a signal generated by the speaker counter-EMF, fed back into the amplifier.

16th century), the author of the "Zarlin Scale," also called "the physicists scale" or diatonic scale; the discussions and research with regard to the tempered scale and the exact pitch of the twelve tones of which it is composed; the work of Marin Mersenne, the author of a famous piece titled "The universal harmony"; or the often quoted works of Herrmann von Helmholz published in 1862 under the title *On the sensation of Tone*.

It is from this work that we can extract a fundamental characteristic of our auditory perception system: the degree to which intervals within an octave are harmonic or dissonant. We also owe a debt of gratitude to other researchers such as Fletcher, Zwicker, S. S. Stevens, and Steinberg, whose important work deals with frequency differences between pure tones and their degree of consonance or dissonance. This research greatly facilitates the study of the subjective influence of harmonic distortion generated by an amplifier.

We are especially indebted to two researchers, Wegel and Lane, for an important basic study from 1930 on the analysis of amplifier harmonic distortion and its subjective influence. These scientists determined with great precision the respective level of each harmonic enabling us to perceive—thanks to the effects of successive masking and multiple harmonics—the illusion of a pure tone devoid of any harmonic distortion. They concluded that for a fundamental of 400Hz, heard at a level of 76dB SPL, the 2nd, 3rd, and 4th harmonics need to have a level of 61dB, 58dB, and 50dB to be audible.

The means available at that time did not allow analysis of harmonic levels of higher order. These experiments could only be realized from 1960, at which time it was shown that for harmonics of order 15 to 20, these harmonics play a role even at levels less than 0.0008% of the total emitted acoustic energy! Together, these well-executed studies allow us to understand why amplifiers, however perfect they may appear in measurements, still produce large distortion, and specifically a very unstable form of distortion because it results from a signal that essentially consists of musical transients. It also explains why certain tube amplifiers (but not all, far from it!) or some transistorized amplifiers reproduce very beautiful, very harmonic sound.

However, these findings must be taken in context. Consider the fact that both an amplifier and a loudspeaker consist of several stages connected in series and also in loops. Each of these stages gives rise to its own specific type of distortion which is fused with that of the other stages, thus forming a global system that is impossible to comprehend in the lab once the sinusoidal signal is replaced by music.

"SOFT" AND "HARD" DISTORTION

Figures A through ***D*** show a few characteristic examples of harmonic distortion as a function of output power for three basic frequencies covering almost the complete audio band, namely, 40Hz, 1kHz, and 10kHz. Curve A, called "soft" distortion, is often found among amplifiers lacking feedback. You can recognize it by a distortion level which is not very small, but increases in a very regular way as a function of the increase in power output.

The best among them have the advantage of producing the same distortion at the same power level over much of the audio frequency band. The majority of the amplifiers that produce this "soft" distortion also show "soft" clipping. When clipping a sinusoidal signal it becomes a curve whose peaks are not cut off but only lightly flattened, which makes the onset of saturation much less audible. The curve in ***Fig. B***, called "hard" distortion, which is more common, generally results from a high level of feedback. The harmonic distortion level is low or even very low over most of the audio band.

Harmonic distortion rises when the level approaches the saturation point, the peaks of a sinusoidal signal almost always forming a flat, cut-off shape, generating higher order harmonics and a very objectionable sound. Curve C corresponds to an amplifier in which the nonlinearities cause an increase or a decrease in harmonic distortion levels at certain frequencies and certain power levels. You may find this (but not always) in circuits equipped with power MOSFET transistors, active components whose known disadvantage is the high input capacitance. You can also find it in hybrid topologies in which the distortion generated by one stage is partially compensated by the distortion of another stage, of which the audible quality varies case by case. You'll find curve D in any type of amplifier, tube, transistor, or hybrid. It results in distortion levels much higher at higher frequencies, which can, in many cases, produce a sound that is hard, gritty, or objectionable.

SUPPLY INSTABILITIES

The majority of amplifiers rely on a basic supply circuit, consisting of a supply transformer with one or two secondary windings connected to rectifier circuitry followed by a capacitor filter or by RC or LC pi-filters. Because the supply is usually common to both channels and connected to each stage forming an amplifier channel, the input of a signal to the amplifier being amplified stage by stage has the secondary effect of generating a myriad of different current draws, shifted in phase or delayed, which will be combined with secondary effects related to different phenomena and to several components, such as:

- various inertias related to charge and discharge times of the filter capacitors
- transient behavior of the supply transformer, the rectifier diodes, and mains filters

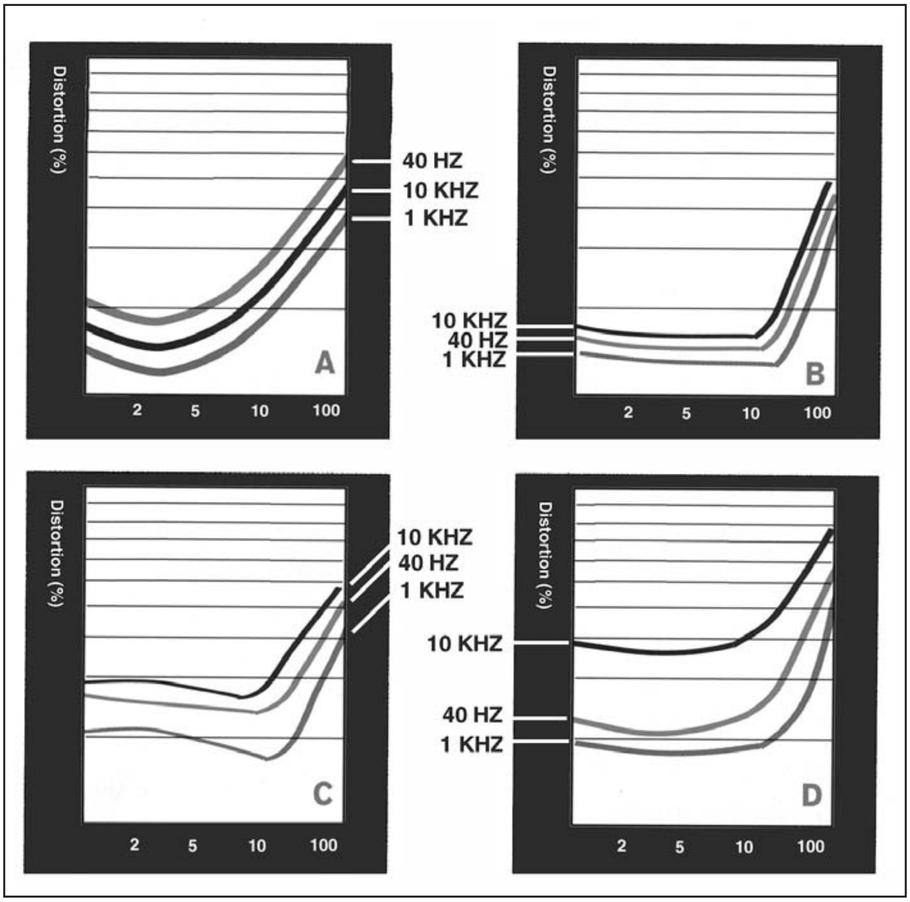

FIGURE A: Soft distortion. Often found in equipment without feedback.

FIGURE B: Hard distortion. The classical case, with a rapid rise near the saturation point.

FIGURE C: Irregular distortion. Due to partial cancellation of the distortion at certain power levels.

FIGURE D: High-frequency distortion. Similar to *Fig. B*, but with higher distortion at higher frequencies.

• variations in the magnetic field emitted by the supply transformer and possible influences on the audio circuits

• irregular behavior of the supply if frequencies directly related to the mains frequency (for example, 50Hz, 100Hz, 150Hz) are being amplified

• Rattle-like phenomena, resulting from a cascade of transient signals (high-level impulses) that leave residual instabilities

• sagging, often very strongly, of the supply voltage in a loaded state (which could reach 50V in badly stabilized tube amplifiers), with the severe consequence of an instability in the different operating points of each amplification stage followed by inertia phenomena related to the charging time of the filter capacitors.

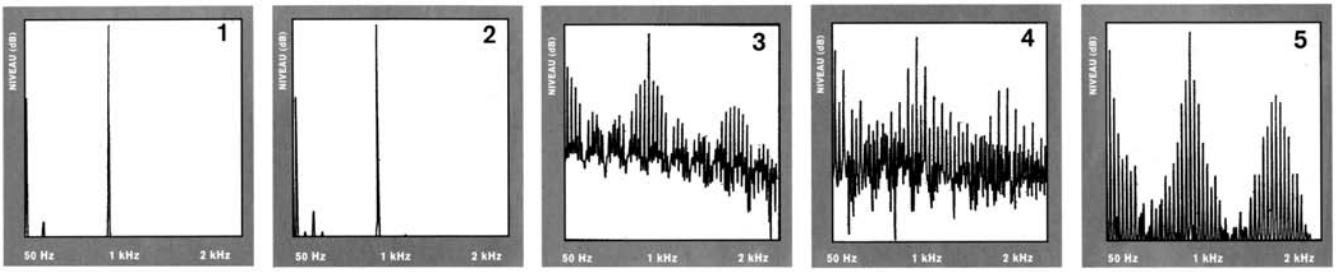

FIGURE 3: Comparative spectral analysis of amplifiers subjected to the transitory IIM distortion under load conditions shown in Fig. 2.

a. *Curve 1*: Original composite signal with its two components at 50Hz and 1kHz;

b. *Curve 2*: Output signal of an amplifier presenting a very good performance at this test;

c. *Curve 3*: Output signal of an amplifier with excellent classical test results for harmonic and IM distortion (less than 0.008% at half power over most of the audio band), but showing strong instabilities in this test, which could be the cause for its "unexplainable" displeasing sound;

d. *Curve 4*: Output signal of the same amplifier as in *Curve 3*, but at higher power. We see that the nature of the instabilities has increased and changed, predicting unstable behavior at other power levels and frequencies;

e. *Curve 5*: A tube amplifier with low feedback, with harmonics and sub-harmonics of the two test signals standing out.

You can easily verify this type of distortion generated by the supply based on the experiences with the circuit in ***Fig. 1***. It consists of extracting from an amplifier fed by a music signal (by using an isolation capacitor) the AC instability component from the supply, amplifying it, then feeding it into the input of another amplifier to listen to the spectral composition and amplitude envelope of that component. Subject to a listening test, this signal can take various forms: muted, sharp, or shrill. It can—as the amplifier includes this or that regulator or certain types of circuits—generate distortions emitted like salvos, by bursts during transients, making you think of a tuner being slightly mistuned next to a radio station.

POWER INTERFACE IIM

We all know Matti Otala, a Finnish researcher who discovered the origin of an obscure type of distortion, Interface Intermodulation Distortion (IIM). This new form of distortion, found as a result of a new measurement method, is caused by the amplifier design: the bandwidth of each stage, group propagation time, delay introduced by the various stages with impact on the feedback loop action during transients. Among the different measurement schemes proposed to prove the existence of this type of distortion, there is no lack of interest in those that simulate the appreciable energy caused by the counter-electromotive force of the loudspeaker and the acoustic enclosure, which is re-injected—not as a voltage but as an energy—into the output of the amplifier—while the amplifier itself is reproducing a different frequency.

Actually, the classical distortion measurements (harmonic distortion, intermodulation distortion according to the SMPTE norms) do not allow detecting it. The basics of this method, which was proposed about 20 years ago by a team of researchers from the University of Musashi, Tokyo, are still relevant today. They are depicted, with some extensions, in ***Fig. 2***.

The method consists of injecting a 1kHz signal at the input of the amplifier under test to obtain a nominal 15W power into the load at the output. This is either a pure resistive 8Ω load or a loudspeaker. A low output impedance power generator, in turn, through a non-inductive 250Ω/1000W resistor and an LC filter to suppress the 1kHz band (self-induction of 7.5mH/15A plus capacitor 3.3μF), inserts a 50Hz signal into the terminals of the load or the loudspeaker. You thus recover the composite signal present at the load or loudspeaker terminals. This signal is then fed into an audio spectrum analyzer.

As shown in the figure, the composite signal is returned to the amplifier and its input, because it contains a feedback loop. By injecting a second signal into the load, with a frequency much lower than the signal being amplified, the counter-electromotive force is simulated which the loudspeaker would inject into the amplifier.

This secondary signal follows very

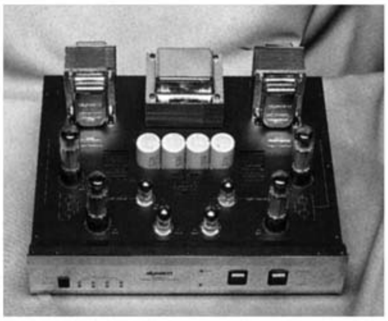

PHOTO 4 (top)**:** Amplifier concept 1: An integrated Rotel amplifier, defending the colors of transistor equipment.

PHOTO 5: Amplifier concept 2: A Dynaco amplifier which represents, with flourish, the virtues of tube amplification.

closely in the time domain and the amplitude domain the envelope of the signal being amplified, and is then more or less quickly attenuated and quickly decreases in frequency. These two effects are the result of the electromechanical damping of the moving mass, the air load of the membrane, and the mechanical friction which slow down the movement until the moving parts return to their rest position.

Curve #1 in *Fig. 3* shows the original composite signal across the purely resistive load, on the left side the 50Hz signal, and a small residual harmonic (100Hz) from the low-frequency power generator. Curve #2 shows the result from a high-quality amplifier with no IIM distortion phenomena whatsoever. Curve #3, on the other hand, shows an amplifier having excellent harmonic and intermodulation distortion figures (like an average value of 0.008% at half power in the middle of the audio band and slightly more above that) but showing, under these test conditions, large problems of IIM distortion under power.

It is interesting to note, in passing, that this same amplifier, when tested with a slightly larger power output, changes its behavior and produces, as seen in curve #4, an even higher IIM with a completely different shape than in curve #3. The fact that these results vary widely from one amplifier to another makes us wish to know its impact on the sound reproduction quality of each.

It has been effectively shown on the spectrum analyzer that listening to amplifiers with anomalies as bizarre as those seen in curves #3 and 4 have a lack of finesse, bad timbre, or sound inexplicably "hard." However, many tests have shown that amplifiers with relatively high distortion levels because of low feedback factors can present, in this type of power IIM distortion, strong disruptions without being unpleasant to listen to—far from it. That is the case for the model of which the measurement is shown in curve #5, a mono triode amplifier equipped with a 10A/801A triode.

Curve #5 shows elevated distortion

levels, with a 2nd harmonic at 2kHz and harmonics of the 50Hz signal, all without any other distortions like those in curve #3. Despite these apparent defects, this amplifier reveals itself in listening sessions to be at least as good as the one shown in curve #2. Anyway, you should not lose sight of the fact that you are measuring two conceptually very different pieces of equipment, of different nominal power, for which the other types of distortion hardly have a chance to be the same.

Dozens of pages would not be sufficient to examine one by one the different distortion types generated by an amplifier and by the amplifier-loudspeaker combination. That is the reason for the importance of critical listening sessions under a strict protocol, despite its limitations and risks of errors, which is seen as the only evaluation method based both on a musical signal as well as simultaneously taking into account a large number of parameters. ■

1. Reprinted and translated from *Revue du Son & du Home Cinema*, Nov. 2003, "La Distortion dans tous ses états."

2. Translating (or rather transculturizing) this article from French into English, neither of which is my mother tongue, has been an interesting experience. I am indebted to Pascale Genet of the School for French as a Foreign Language in Montpelier, France (www.lefrancparler.fr), for numerous tips and corrections.