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The Mud Factor

An inquirer posed the question "Why should I buy speakers costing $800 each when I could buy some crummy little speakers and tailor the response of both speaker and room with a 'voicing' device"? (I retain the questioner's vocabulary).

This looks like a simple question. The answer is not as simple.

And lets pose another question, Why do equipment reports rate the modulation distortion in amplifiers (often in hundredths of a per cent), but ignore the modulation distortion in loudspeakers which is rarely less than one per cent and often in dozens of per cent?

The attributes of a loudspeaker, in order of importance, are:

(1) Total Distortion, at a given acoustic power *output* level
(2) Polar Response
(3) Amplitude vs. Frequency response
(4) Harmonic Distortion

To give a quick and dirty answer to the first question, the "crummy speaker" will still be crummy after its frequency response has been flattened to ±4 dB, or ±2 dB, or zero dB, because its diaphragm has to move through large excursions to produce a desirable bass output, and the upper frequencies are subject to modulation distortion in direct proportion to how far the diaphragm moves.

The second question remains unanswered.

Which gets us to the kernel of the nut, Modulation Distortion.

Modulation Distortion

Let distortion be defined as the generation of frequencies not originally present. Thus it is distinguished from frequency response errors and the two may be measured and discussed separately.

Harmonic Distortion (hereafter abbreviated HD) is the introduction of harmonics of the original frequencies. This is not objectionable in the reproduction of music which is full of harmonics to begin with and the introduction of even considerable amounts of HD would merely alter the ratios of harmonics already present.

Hilliard[1] wrote that measurement of frequency response and harmonic distortion do not yield a true measure of quality. A single musical instrument transmitted through a system with harmonic distortion will be reproduced with a slightly altered harmonic content and the distortion will go unnoticed. But when a group of sources is reproduced, the effects of non-linearity introduce modulation ('inter" modulation) distortion consisting of sum and difference frequencies which are not harmonically related to the original sounds and which are harsh. Such distortion is far more disagreeable than is harmonic distortion in similar amounts. Further it has been shown that modulation distortion usually exceeds harmonic distortion; Hilliard remarks "As the intermodulation test is approximately 4 times as sensitive as the harmonic analysis method, it approaches the sensitivity of the ear in detecting intermodulation effects and it is a very valuable tool with which to measure distortion. By comparison, other methods are inadequate and inconvenient, as well as more laborious."

Applied to amplifiers, the modulation (pardon me if I drop the "inter") test has gained wide acceptance since 1941.

Scott[2] points out that many writers have realized that modulation distortion and not harmonic distortion is responsible for the annoying quality in amplifiers. A small percentage of harmonic distortion does not in itself produce a serious change in sound quality. But when two different tones are simultaneously amplified under conditions of distortion the modulation results in sum and difference frequencies which are not harmonically related to the original tones. He remarks that some writers ignore modulation distortion as negligible, but points out as an example the soprano with flute obbligato "reproduced with addition of growling difference frequencies." Recall that Scott was writing in 1945.

But loudspeakers display typically many times the total modulation distortion of amplifiers. Considering quality levels of 1970, the better amplifiers display total distortion in the order of 0.2 per cent or less. The best loudspeaker so far measured at a "moderate" output level (100 dB at 2 feet) displayed nearly one per cent, and lesser speakers at the same or lower output levels (90 to 95 dB) displayed up to 30 per cent. Examples will be given of speakers displaying 14 per cent distortion.

TABLE I

COMPARISON OF LOUDSPEAKER DISTORTIONS

Frequencies: 42 and 310 Hz	Output SPL at 2 ft.	Distortion Per Cent
Large Horn Loudspeaker	100	1
Small Direct Radiator	98	10
"Bookshelf" Speaker System	95	14+

In amplifiers only one form of modulation distortion exists, namely amplitude-modulation distortion (AMD). In loudspeakers frequency-modulation distortion (FMD) due to the Doppler effect, and AMD both exist.

The "crummy" speaker of our inquirer might be one that has been found to have 10 per cent or more modulation distortion. No amount of tailoring the response curve can reduce the distortion.

Frequency-modulation distortion (FMD) arises in a loudspeaker when the motion of a loudspeaker diaphragm at some low frequency, f_1, causes a higher frequency, f_2, to deviate due to the Doppler effect, resulting in the same kinds of sideband frequencies produced by AMD, namely $f_2 \pm f_1$, $f_2 \pm 2f_1$, etc.

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Frequency Modulation Distortion

Beers and Belar[3] give

$$d = 0.033\, A_1 f_2 \qquad (1)$$

where d is the effective amplitude of the spurious side-band frequencies, in per cent of the amplitude of f_2; A_1 is the amplitude of diaphragm motion in inches at the lower frequency f_1, and f_2 is the higher frequency being modulated.

With the availability of spectrum analyses the examination of the output of a speaker involves a few seconds of time. One must be forced to admire the work of Beers and Belar who had to "do it the hard way" to obtain meaningful test data on loudspeakers.

Amplitude Modulation Distortion

Modulation distortion in amplifiers has long been recognized as something to be minimized. Originally referred to as intermodulation distortion, I prefer to drop the "inter" prefix: modulation distortion requires two or more frequencies so that one may modulate another, hence the term modulation distortion should suffice. Typically high-quality amplifiers of 1970 as reviewed in various magazines devoted to "high fidelity" are rated in hundredths of one per cent AMD. And the closer to zero they get the more the customers complain that "Amplifier A sounds better than Amplifier B" when both exhibit a tenth as much distortion as the best loudspeakers through which the amplifiers are judged.

Loudspeaker Tests

A relatively few years ago the analysis of a complex wave was a matter of many hours work with a "harmonic analyzer," where each frequency component was sought out and measured. With a spectrum analyzer, the pertinent part of a spectrum may be examined in a matter of seconds. When the early papers were written, the analysis of speakers or amplifiers in detail represented a monumental amount of labor. Now the actual analysis may take 40 seconds, and the labor is mainly that of furniture moving.

In the case of amplifiers, the modulation testing involving two frequencies, say 30 to 60 Hz and 6000 Hz would normally suffice. In loudspeakers a considerable number of pairs of frequencies are needed, particularly in 2-way and 3-way speaker systems. For example, consider a 3-way system with crossover points of 500 and 5000. Use of 50 and 2000 Hz would radiate the two frequencies from different diaphragms so the modulation distortion might appear to be negligible. But applying 50 and 300 will cause the two frequencies to be radiated from the same diaphragm and they will interact. Even with high-quality loudspeakers a perceptible flutter will be audible if the power output is great enough, (say considerably in excess of 100 dB SPL at 2 feet).

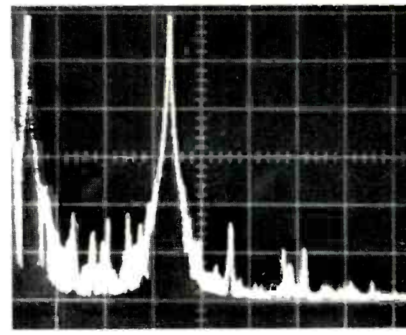
In amplifier testing, the two frequencies are usually mixed in the amplitude ratio of 4:1, the idea being that the power output requirement at 6000 Hz is much lower than at some frequency in the first three octaves. In loudspeakers, the woofer is required to deliver substantially its whole spectrum at high levels, so in testing bass loudspeakers, I prefer to choose two frequencies at the same power level (output) within the pass band of the bass speaker.

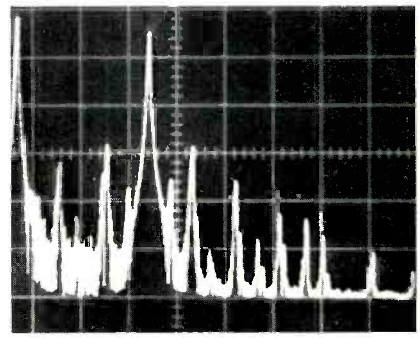
A number of loudspeakers have been measured with particular attention to modulation distortion.[4, 5] As would be expected from equation (1), speakers exhibiting the smallest total diaphragm excursion displayed the least modulation distortion. Well-designed horn-type speakers combine the advantages of smooth frequency response and low distortion. Even so, the best loudspeakers exhibit upwards of one per cent total modulation distortion, compared to tenths of a per cent for TMD (or IMD) in amplifiers.

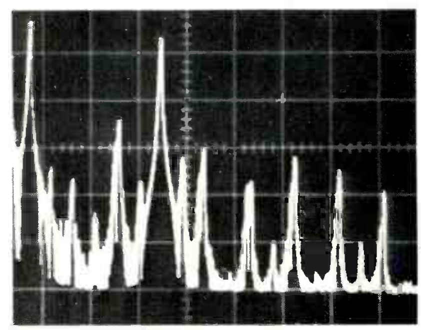
The cited references give several examples of bass, midrange, and tweeter speakers. For the present discussion, three examples of bass speakers will be used.

Figure 1 is a spectrogram of a large bass speaker of the highest quality. The picture has been trimmed to put zero frequency at the left edge. (The spectrum analyzer used produces a zero frequency marker). The first peak, f_1, is 42 Hz at 100 dB SPL at 2 feet. The second major peak is 310 Hz at the same output level. The minor peaks are distortion frequencies introduced by the speaker. The horizontal scale is linear. The vertical scale is 10 dB per division. All the spurious frequencies $f_1 \pm f_2$, $f_1 \pm 2f_2$, etc., are at least 40 dB down from the amplitude of f_1, but this still represents about one per cent distortion for the very finest of loudspeakers.

Figure 2 is the spectrogram of a 12-inch direct-radiator driver unit in a total enclosure of about 1.5 ft^3. This displays side-band frequencies of $f_2 \pm 2f_1$ about 23 dB down from the amplitude of f_2 (7 per cent) with root-mean-square total distortion of about 10 per cent. This speaker is regarded as "excellent in its price class" but muddy at any but very low volume levels. Note the extensive family of even-order side-band frequencies. The output level of 100 dB was about the upper limit before displaying "gross" distortion in the form of knocking sounds. The inner voices







In all the figures f_1=42 Hz
f_2=310 Hz
Represented by the two major peaks
Vertical scale 10 dB per division.

Fig. 1—High-quality woofer of large size: f_1 and f_2 output, 100 db SPL at 2 ft.
All modulation-distortion components are 40 dB or more down from the peaks of f_1 and f_2, representing 1% maximum for the worst component.

Fig. 2—Twelve-inch direct radiator in 1.5 ft^3 total enclosure.
f_1 at 100 dB SPL at 2 feet
f_2 at 95 dB SPL at 2 feet.
Side-band frequency components of second order ($f_2 \pm 2f_1$) are 23 dB down from amplitude of f_2 (7%) and the RMS sum is 10%.
There are six other side-band frequencies exceeding −40 dB or 1% of the amplitude of f_2.

Fig. 3—Eleven-inch direct radiator in small total enclosure.
f_1 at 98 dB at 2 feet
f_2 at 94 dB at 2 feet
Side-band frequencies represent over 14% RMS total modulation distortion.

of ensembles are obscured by spurious frequencies and reproduction by such speakers is called "Muddy". The ratio of these distortion products to the desired signal has been called "The Mud Index".

Figure 3 is the spectrogram of an 11-inch driver unit in a small total enclosure. Here second-order side bands are still larger (17 dB down or 14% for the most prominent component) and again displaying an extensive family of even-order sideband frequencies. In this speaker, the output amplitudes of f_1 and f_2 were 100 and 95 dB respectively.

The point of all this is to attempt to indicate the importance of modulation distortion in loudspeakers. If amplifier manufacturers deem it important to achieve (and advertise) "total distortion including modulation less than 0.25%" it is obviously ridiculous to ignore 100 times that much distortion in loudspeakers!

With 10 or more spurious side band frequencies being generated out of the two input frequencies, consider how a musical ensemble would be cluttered. The inner voices become submerged in a sea of mud. To ignore this form of distortion is to ignore the fact that some speakers are just plain muddy.

Just how important modulation distortion is can not be overemphasized. Since the modulation products are inharmonic relative to the signal, their power to irritate is large compared to that of simpler harmonic distortion. Furthermore, the amplitude of the modulation-distortion components is greater than the amplitudes of the harmonic distortion. Warren and Hewlett[6] show that the ratio of amplitude-modulation distortion to harmonic distortion in amplifiers ranges from a value of 1 up to over 4, and is ususally more than 3. The same forms of non-linearity exist in loudspeakers as in amplifiers, and the same analysis holds, so the AMD-to-HD ratio for loudspeakers must be of the order of 3 or more. Then the frequency-modulation distortion, not present in amplifiers, must increase this ratio of modulation to harmonic distortion by an appreciable amount. Without the spectrograms it should have long been obvious that modulation distortion is an important fault in loudspeakers; with the spectrograms the proof should be evident for all who care to see.

Conclusion

With loudspeakers displaying from 10 to 100 times as much modulation distortion as the best amplifiers, wouldn't it seem logical to include modulation-distortion tests of speakers instead of relying on a listening comparison between speakers and perhaps a response curve under non-specified conditions? I think the reviewers should be challenged to review loudspeakers with the same types of tests applied to amplifiers, including the one test—modulation distortion—which really separates the sheep from the goats.

Finally, "Muddiness" is the opposite of "Clarity." The speakers analysed may be summarized, calling the per cent total modulation distortion at the specified sound-pressure level the MUD INDEX.

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A highly controversial article and we would be pleased to publish some other points of view on the subject. For instance, Paul mentions the high distortion of loudspeakers compared with amplifiers. Granted, but the fact is that you *can easily* hear the difference between an amplifier with .5% IM and a similar amplifier with 3% IM with loudspeakers having a Klipsch MF of 14% or higher . . . In other words, speaker modulation distortion figures may *look* worse than the resulting sound. Consider this: direct radiator speakers have been used for a number of successful live-versus recorded sound demonstrations and if the 14% figure really meant anything such comparisons would be impossible. Then again, Paul compares direct-radiators with horn-loaded systems which have their own problems. I believe that a theoretically high modulation distortion is more tolerable to most people than a much lower percentage (by measurement) of distortion caused by coloration due to enclosure resonances, horn reflections, peaks in the frequency response and so on. This does not mean that we can dismiss modulation distortion as being of no significance, but it *does* indicate that more research is needed to assess the subjective effects compared with other types of distortion preferably using more complex signals than sine waves.—*Ed.*