Modulation Distortion in Loudspeakers: Part II

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Modulation distortion in loudspeakers consists of amplitude modulation distortion (AMD) and frequency modulation distortion (FMD); the effective sum of these is the total modulation distortion (TMD). It appears that the first-order side frequencies are due mainly to frequency modulation and the second-order sideband frequencies are due to amplitude modulation. Small direct-radiator loudspeakers typically display large AMD and relatively less FMD, while horn loudspeakers display small FMD and negligible AMD.

INTRODUCTION Part I of this paper [1] defined the various kinds of distortion. The previous paper was concerned mainly with frequency modulation distortion (FMD), which appeared to be of greater importance than amplitude modulation distortion (AMD). Applying the spectrum analyzer to small direct radiators shows that AMD may exceed FMD by an order of magnitude.

ANALYSIS

A former colleague suggested that in a symmetrical system first-order sideband frequencies would not exist [2].

Let

$$y = k(x - mx^3) \tag{1}$$

and assume this to be a reasonable approximation to the displacement y of a loudspeaker diaphragm for an applied force of x, to be considered valid over the range of

$$-2.0 < x < +2.0$$

Figure 1 illustrates this "stress–strain diagram", where, for example, $m = 0.1$, or

$$y = k(x - 0.1x^3). \tag{2}$$

Now assume two equal sinewaves of unit amplitude,

$$x = \sin\omega_1 t + \sin\omega_2 t \tag{3}$$

$$\begin{aligned} y = {} & \sin\omega_1 t + \sin\omega_2 t \\ & -0.1\,[\sin^3\omega_1 t + 3\sin^2\omega_1 t \sin\omega_2 t \\ & + 3\sin\omega_1 t \sin^2\omega_2 t \\ & + \sin^3\omega_2 t]. \end{aligned} \tag{4}$$

Using $\sin^3 a = 3/4 \sin a - 1/4 \sin 3a$; $3 \sin^2 a \sin b = 3\,(1/2 - 1/2 \cos 2a) \sin b + 3\,(1/2 - 1/2 \cos 2b) \sin a = 3/2 \sin b - 3/2 \sin (a + 2b) - 3/2 \sin (a - 2b)$, etc., we obtain

$$\begin{aligned} y = {} & \sin\omega_1 t + \sin\omega_2 t \\ & -0.1\,[3/4 \sin\omega_1 t - 1/4 \sin 3\,\omega_1 t \\ & + 3/4 \sin\omega_2 t - 1/4 \sin 3\,\omega_2 t \\ & + 3/2 \sin\omega_1 t + 3/2 \sin\omega_2 t \\ & - 3/2 \sin(\omega_1 t + 2\,\omega_2 t) \\ & - 3/2 \sin(\omega_1 t - 2\,\omega_2 t) \\ & - 3/2 \sin(\omega_2 t + 2\,\omega_1 t) \\ & - 3/2 \sin(\omega_2 t - 2\,\omega_1 t)], \end{aligned} \tag{5}$$

or

$$\begin{aligned} y = {} & 0.775 \sin\omega_1 t + 0.775 \sin\omega_2 t \\ & + 0.025\,(\sin 3\,\omega_1 t + \sin 3\,\omega_2 t) \\ & - 0.15\,[\sin(\omega_1 t + 2\,\omega_2 t) \\ & + \sin(\omega_1 t - 2\,\omega_2 t) \\ & + \sin(\omega_2 t + 2\,\omega_1 t) \\ & + \sin(\omega_2 t - 2\,\omega_1 t)]. \end{aligned} \tag{6}$$

second-order sidebands of f_2 are below the resolution of the spectrum analyzer, it is to be assumed that amplitude modulation is negligible and that the sidebands are due to FMD.

The lower curve in Fig. 2 shows the spectrogram of the 8 in. direct radiator. As in the top figure, the first peak is the amplitude of f_1, but followed by small amounts of second and third harmonic distortion. Next is a large peak, amplitude of f_2, flanked by first- and second-order sideband amplitudes. Then comes the second harmonic $2f_2$ flanked by its sidebands of $2f_2 \pm f_1$, and finally $3f_2$. All the components predicted by Eq. (6) are represented. The magnitude of the $2f_2$ component is much larger than would be expected from Eq. (6) and remains unexplained, except that direct-radiator loudspeakers do unexplained things. Perhaps a nodal cone breakup was taking place and the microphone was in just the right place to maximize the fault. The fact that the second harmonic of f_1 predominates over the third harmonic suggests that the first-order sideband amplitudes of f_2 contain both AMD and FMD.

A significant observation is that the direct-radiator midrange loudspeaker had to be driven into a nonlinear range of cone travel to produce 100 dB SPL at 2 ft. This level corresponds to about 90 dB at a normal listening distance in a typical listening room. This is 1/100 the peak sound power one would demand for "realistic music reproduction", but one sees various orders of modulation distortion in amounts up to 15%. By contrast, the high-quality horn loudspeaker shows a mere 1% total modulation distortion at the same output power.

Another significant observation is that the high-quality horn displays only first-order modulation distortion, which is probably the irreducible frequency modulation type. Again, by contrast, the direct radiator shows a much higher level of first-order sideband components, suggesting suspension asymmetry plus higher FMD output.

TEST OF A FULL-RANGE LOUDSPEAKER

The speaker chosen for this test was a direct radiator consisting of several small cone loudspeakers of "long throw" capability and with a total area approximating that of a 12 in. cone loudspeaker. This system was intended for "full frequency range" and normally employed with an equalizer. The two frequencies were f_1 = 50 Hz and f_2 = 750 Hz, both adjusted to produce 95 dB SPL at 2 ft.

Figure 3 shows the spectrogram of this test. The first peak is the amplitude of the output of f_1. Following this, barely discernible, is the second harmonic ($2f_1$), followed by a strong $3f_1$ (about 20 dB down or 10% third harmonic). Fourth and fifth harmonics are significant.

The next major peak is f_2 (same amplitude as f_1, 95 dB) flanked by small (−30 dB) first-order sidebands ($f_2 \pm f_1$), in turn are flanked by larger second-order sidebands ($f_2 \pm 2f_1$). Still higher-order sidebands are visible.

From an analysis such as Eq. (6), and from the earlier paper, it would appear that there is about 3% FMD and 14% AMD. Apparently the FMD is not as serious as the AMD for this particular loudspeaker.

Sidebands of order higher than the second are not explained by Eq. (6); however, the derivation assumed symmetry, and some asymmetry existed as indicated by presence of a second harmonic of f_1.

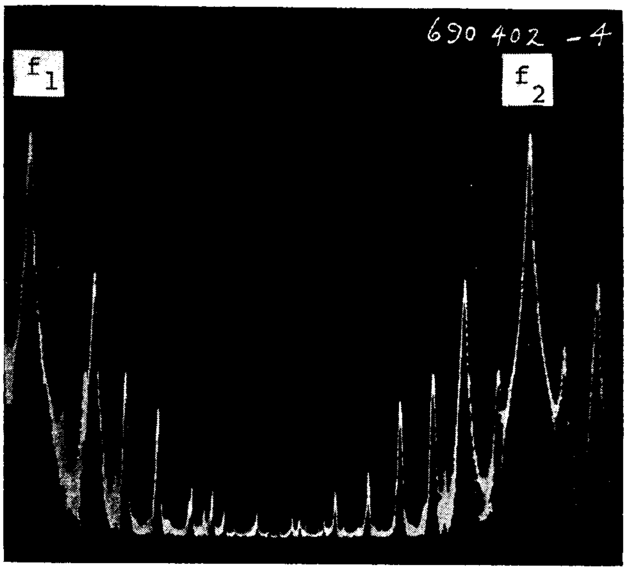


Fig. 3. Spectrogram of small full-range direct radiator employing several small cone loudspeaker elements and a preamplifier equalizer. First peak f_1 = 50 Hz, followed by a small $2f_1$ component, and $3f_1$, $4f_1$, etc. Second large peak, f_2 = 750 Hz, flanked by small first-order sidebands of $f_2 \pm f_1$ and larger sidebands of $f_2 \pm 2f_1$, and significant third- and fourth-order sideband frequencies. Total modulation distortion, approximately 14%. Input of both frequencies adjusted to produce 95 dB SPL at 2 ft.

It is easy to ignore sideband amplitudes of less than 3% when there are distortion amplitudes exceeding 10%. It would be interesting to find the causes of these unpredicted distortion products, but the cone loudspeaker with its infinite number of modes of vibration and breakup could take a lifetime of studying third order effects.

DISCUSSION

Beers and Belar [3] suggested using different speakers for bass and treble. An examination of Fig. 2 suggests that this expedient does not go far enough. Here is an example of a direct-radiator midrange loudspeaker such as is used in a three-way system, producing excessive distortion within its own normal band. The horn-loaded loudspeaker displays about 1/10 the distortion of the direct radiator.

In the case of the multiple loudspeaker whose performance is shown in Fig. 3, obviously the mere proliferation of the number of loudspeakers fails to reduce distortion to tolerable levels. In the companion paper a horn woofer was tested at 100 dB SPL and found to produce less than 1% total modulation distortion.

The frequency response curves of the three loudspeakers tested are shown in Figs. 4 and 5.

The solid curve in Fig. 4 shows the frequency response of the horn midrange, the distortion of which is shown in Fig. 2a. The partly dashed curve in Fig. 4 is for the direct radiator depicted in Fig. 2b.

Figure 5 shows the response (including equalizer) of the loudspeaker whose distortion is depicted in Fig. 3.

One should not expect a correlation between distortion

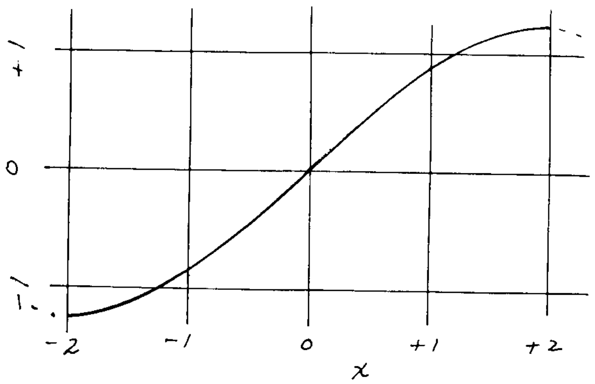


Fig. 1. Simplified stress–strain (force *vs* displacement) curve for suspended system of a loudspeaker, assuming symmetry of both magnetic and compliance systems.

The bracketed term in Eq. (6) shows modulation sideband frequencies of $f_1 \pm 2f_2$ and $f_2 \pm 2f_1$.

Note that these are second-order sidebands; there are no first-order sidebands of the form $f_2 \pm f_1$.

One may conclude that in a symmetrical system, such as illustrated in Fig. 1, only second-order amplitude-distortion sideband frequencies exist.

In Part I of this paper [1], an example was used wherein the amplitudes of the frequency modulation sideband frequencies were 0.017 (1.7%) for the first order and 0.00013 for the second order. These second-order amplitudes are 40 dB down lower than the first-order ones and not apt to show on an analyzer spectrogram.

Thus it appears that first-order sideband amplitudes can be attributed mainly to frequency modulation distortion and second-order sideband amplitude entirely to amplitude modulation distortion.

Of course, asymmetric nonlinearity would induce some first-order AMD, but it would seem that any second-order sideband frequencies must be almost entirely due to AMD.

INTERPRETATION

Examining Eq. (6) further, the fundamental signals, f_1 and f_2, which started out at unity are reduced to 0.775. There is a 2.5% third harmonic of each input signal. These effects are intuitively obvious, at least qualitatively. The amplitude of each sideband frequency which reads 0.15 amplitude becomes approximately 19% of the 0.775 fundamental output.

The bracketed terms show amplitudes of frequencies $f_2 \pm 2f_1$. This indicates that the symmetrical stress–strain systems depicted in Fig. 1 give rise to second-order sidebands, with complete absence of first-order sideband frequencies of $f_2 \pm f_1$.

The bracketed terms show amplitudes of frequencies of $f_1 \pm 2f_2$. Recognizing that $\sin(-a) = -\sin a$, it is logical to conclude that, with appropriate phase shifts, these sideband terms may be written as amplitudes of $2f_2 \pm f_1$.

This turns out to be a surprise. Early work with the sprectrum analyzer did not show these high-order terms for the simple reason they were not suspected and the "window" of the analyzer was not wide enough to include them. Therefore, in some of the new study the analyzer was adjusted to "see" out past $3f_2$.

TESTS OF MIDRANGE LOUDSPEAKERS

Two midrange loudspeakers were compared. One was a horn-loaded system designed for the 400 to 6000 Hz range, the other was an 8 in. direct-radiating cone designated by its manufacturer specifically for midrange application. Frequencies of $f_1 = 540$ Hz and $f_2 = 4400$ Hz were used, and inputs adjusted to give outputs of 100 dB SPL at 2 ft for f_1 and 92 dB for f_2. The vertical scale is 10 dB per major division.

Figure 2 shows the two spectrograms. The upper curve depicts the performance of the horn loudspeaker: the first peak is the amplitude of f_1, and no harmonics of f_1 are seen. The next large peak is the amplitude of f_2, flanked by two small first-order sideband amplitudes. The sideband amplitudes are nearly 40 dB below the amplitude of f_2, so that the total modulation distortion is slightly over 1%.

Since harmonic distortion of f_1 is not visible and

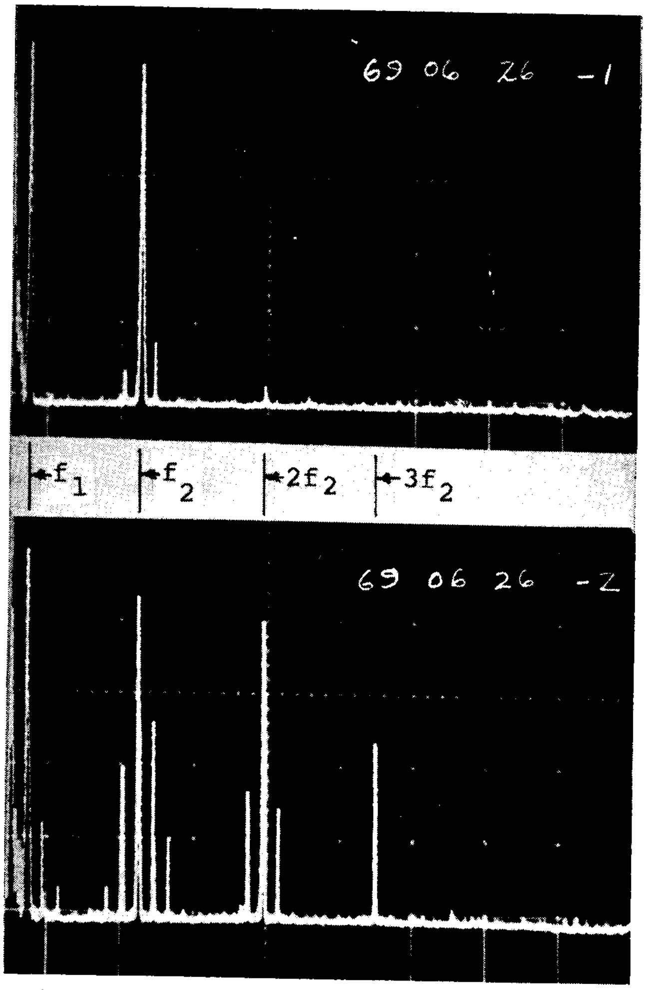


Fig. 2. Spectrograms of *a*. horn and *b*. direct-radiator midrange loudspeakers. Output 100 dB SPL at 2 ft for $f_1 = 540$ Hz, 92 dB for $f_2 = 4400$ Hz. Vertical scale 10 dB per major division. First two major peaks are f_1 and f_2. In top figure, the only significant distortion showing is the pair of sideband frequencies $f_2 \pm f_1$. In the bottom figure significant distortion components are $2f_1$, $f_2 \pm f_1$, $f_2 \pm 2f_1$, $2f_2$, $2f_2 \pm f_1$, and $3f_1$. Total distortion over 10%.

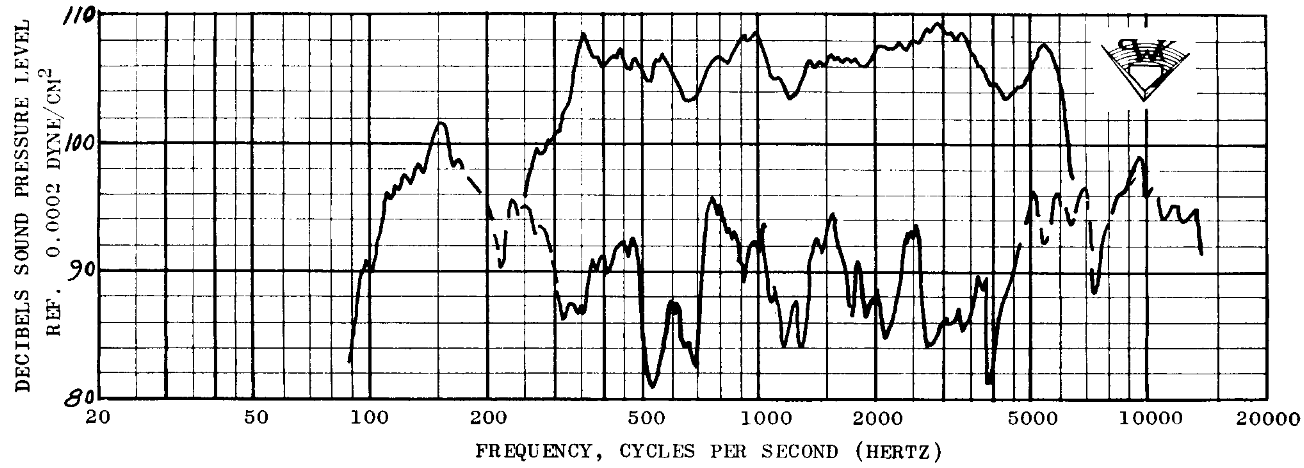


Fig. 4. Response curves of the midrange loudspeakers with distortion shown in Fig. 2. *Top curve*. Horn system; *Bottom curve*, 8 in. direct radiator, both at 1 W input.

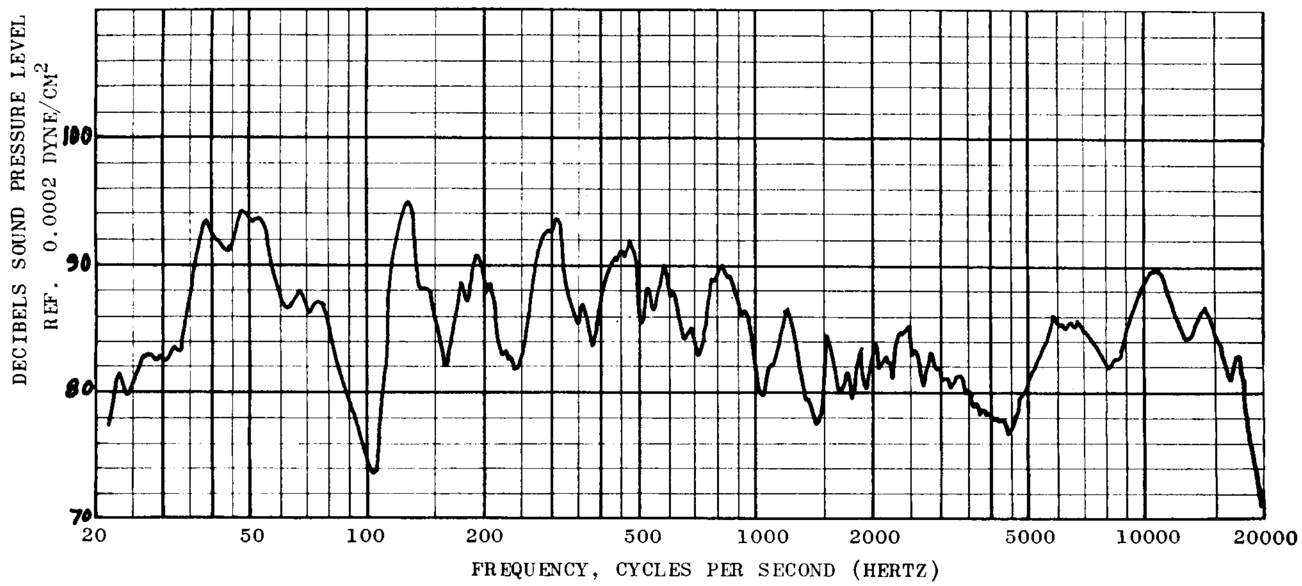


Fig. 5. Frequency response of the loudspeaker with distortion shown in Fig. 3. Input 0.5 W at 500 Hz, approximately 50 W at 40 Hz (difference due to equalizer); curve level coordinates corrected to 1 W input at 500 Hz.

of a loudspeaker and its frequency response, but in these cases it appears the response peak–trough ratio does correlate with the amount of total modulation distortion.

CONCLUSION

It is believed that Figs. 2 and 3 illustrate at least qualitatively what can be concluded from Eq. (6) and from Part I of this paper. The separation of FMD and AMD may not be absolute and precise, but it appears that first-order sideband components must be largely FMD and second-order components largely AMD. Further, it seems to follow that high-efficiency horns will display small FMD and negligible AMD compared to direct radiators, in which both forms of distortion are higher. Small direct radiators driven to output levels necessary for "realistic reproduction of music" may display a preponderance of AMD over FMD, and at objectionably high distortion levels.

A technical conclusion is that, to a reasonable approximation, the spectrum analyzer shows first-order sideband frequency components as FM distortion and second-order components as AM distortion.

A practical conclusion is that the inherently low distortion of properly designed horn-type loudspeakers is significant in the virtual elimination of amplitude modulation distortion and the reduction of frequency modulation distortion to nearly irreducible limits, and that this low distortion is the main contribution to the "cleanness" of sound reproduction from loudspeakers of this type.

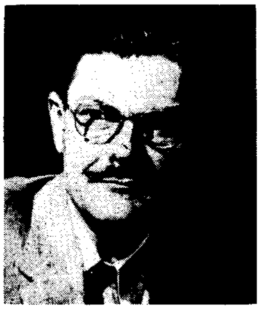
REFERENCES

1. Paul W. Klipsch, Modulation Distortion in Loudspeakers, *J. Audio Eng. Soc.* **17**, 194 (1969).

2. John Eargle, personal communication.

3. G. L. Beers and H. Belar "Frequency—Modulation Distortion in Loudspeakers", *Proc. IRE* **31**, 132 (Apr. 1943).

THE AUTHOR



Paul W. Klipsch was born in 1904, in Elkhart, Indiana. He received the B.S. Degree in Electrical Engineering from New Mexico College for Agricultural and Mechanical Arts in 1926 (now New Mexico State University), and the E.E. from Stanford University in 1934.

He was employed in the testing department of General Electric Company from 1926 to 1928; at the Anglo-Chilean Consolidated Nitrate Corporation, Tocopilla, Chile from 1928 to 1931; the Independent Exploration Company, Houston, Texas from 1934 to 1936, the Subterrex Company, Houston, Texas from 1937 to 1941; and the U.S. Army Ordnance Department from 1941 to 1945 (Major, 1943, Lt. Col., 1953). At present, he is president of Klipsch and Associates, Inc., Hope, Arkansas, a firm which manufactures loudspeakers.

Mr. Klipsch has written many papers and holds patents in the fields of geophysics, acoustics, firearms, etc. He is a Fellow of the Audio Engineering Society, Fellow of IEEE, Member of the Acoustical Society of America, Tau Beta Pi, Sigma Xi, and is listed in Who's Who in Engineering.