How to Graph Distortion Measurements

Preprint 3602 (L1-5)

Steve F. Temme
Brüel & Kjær
Nærum, Denmark

Presented at
the 94th Convention
1993 March 16–19
Berlin

AN AUDIO ENGINEERING SOCIETY PREPRINT

HOW TO GRAPH DISTORTION MEASUREMENTS

Steve F. Temme

Brüel & Kjær
DK–2850 Nærum, Denmark

ABSTRACT

Distortion curves are conventionally plotted under the corresponding excitation frequency of the measured fundamental. Interpretation of results can be misleading due to the influence that the passband shape and amplitude irregularities of the fundamental response have on the distortion responses. By "amplitude normalizing" the distortion responses to the fundamental response before plotting them at the excitation frequency, distortion graphs become easier to interpret for diagnostic purposes. In addition, the distortion curves become insensitive to room reflections in the measured responses.

1 INTRODUCTION

In my previous paper, "Why and How to Measure Distortion in Electroacoustic Transducers" [1], I discuss the importance of measuring distortion using different test methods for different applications. This paper emphasizes the need for a concise and easy to understand presentation of distortion measurement results. People often look for an easy to grasp number, such as the maximum Total Harmonic Distortion (%THD) published on a specification sheet, without knowing the true significance of the number and how it was obtained. Designers, in particular, would like a better idea of what goes on in the mechanical part of the electroacoustic transducer, independent of the linear acoustical radiation of the loudspeaker.

It is possible to condense a lot of information about a transducer's nonlinear performance with respect to frequency, level, and type of distortion, on a few easy to read graphs. At the same time, distortion will be discussed with respect to maximum output level and compression.

2 FREQUENCY NORMALIZATION

By convention, a frequency shift is applied to the measured harmonic responses when plotting harmonic distortion curves on the same axes as the fundamental response [2]. Harmonic distortion responses are normally plotted at the excitation frequency rather than at the actual measured frequency. Many people are unaware of this and may inadvertently draw erroneous conclusions about both the severity and cause of the distortion.

For example, the 2nd harmonic of 20 Hz occurs at 40 Hz and the 3rd harmonic occurs at 60 Hz (Fig. 1). Instead of plotting the harmonic distortion responses at the actual measured frequency (Fig. 2), they are plotted at the corresponding excitation frequency of the measured fundamental, i.e. frequency normalized to the fundamental (Fig. 3). This can lead to some difficulties in evaluation due to the influence that the expected passband shape and any amplitude irregularities of the fundamental response have on the distortion responses. For example, a peak at 1 kHz in the fundamental response will provoke a peak in the 2nd harmonic response at 1/2 the frequency and 1/3 the frequency for the 3rd harmonic response (Fig. 3). When following this convention it is easy to misinterpret the relative distortion level. Typically when viewing such a graph as in Fig. 3, people compare the level of the harmonic distortion curve and the fundamental at the excitation frequency. For loudspeakers in particular, the fundamental response will most likely not be the same amplitude at the harmonics excitation frequency and actual measured frequency (see Fig. 3: 3rd harmonic at 20 Hz). This explains why harmonic components can appear to be higher in level than the fundamental at the low end of the frequency scale and lower in level at the high end of the frequency scale.

Let's look at some real distortion data measured on a small, 2-way, closed-box loudspeaker (see Fig. 4). A simulated free field measurement was performed using a Brüel & Kjær Type 2012 Audio Analyzer. If the harmonics are plotted at the actual measured frequency (Fig. 5), artifacts in the harmonic responses can be easily correlated to irregularities in the fundamental response. For example, there are two distinct bumps between 20kHz – 40kHz, in the fundamental response, which are also obvious in the harmonic distortion responses when plotted at the actual measured frequency. It is important to distinguish between nonlinear effects and linear effects caused by the fundamental superimposed on the harmonic responses. This is necessary if the goal is to identify the mechanisms in the transducer which cause distortion.

3 AMPLITUDE NORMALIZATION

Because distortion is a relative measurement, harmonic responses can be plotted relative to the fundamental, both in amplitude and frequency. This is obtained by dividing the harmonic response at the actual measured frequency by the fundamental response. This result can then be plotted at the corresponding excitation frequency without the passband shape and amplitude irregularities of the fundamental influencing the result. This provides a concise presentation of the measured result for diagnostic purposes (Fig. 6). Remember, the fundamental is 0 dB at each frequency, due to this amplitude normalization.

Notice that the high frequency bumps and dips present in both the fundamental and harmonic responses (Fig. 5) disappear when amplitude normalizing the harmonic responses at their actual measured frequencies to the fundamental response before frequency normalizing (Fig. 6). Amplitude normalization after frequency normalization as in Fig. 7, however, not only creates more peaks and dips, but it also overestimates the distortion level, considerably, for both the 2nd and 3rd harmonic at 50 Hz. The 3rd harmonic is overestimated by 20 dB (from 1% to 10%) at 50 Hz and underestimated by 20 dB (from 0.7% to 0.07%) at 10 kHz. Fig. 7 also underestimates the severity of the distortion level at the crossover frequency of 2 kHz.

4 INFLUENCE OF ROOM REFLECTIONS

In Fig. 4 and 5, the amplitude irregularities in the fundamental response were due solely to the loudspeaker. It was shown in Fig. 6 that it is possible to divide out these anomalies influencing the measured harmonics by amplitude normalizing the harmonic responses at the actual measured frequency before frequency shifting the harmonics to the respective excitation frequency.

If the same loudspeaker is measured in an ordinary room (Fig. 8), room reflections will add considerable amplitude peaks and dips to the measured fundamental and harmonic responses. By plotting the harmonics at their actual measured frequencies (Fig. 9), many of the peaks and dips in the harmonic responses correspond to peaks and dips in the fundamental response.

By following the same procedure as was performed to obtain Fig. 6, very similar results are obtained (Fig. 10), using the fundamental and harmonic responses containing room reflections. Once again, this involves dividing the harmonic response at the actual measured frequency by the fundamental response. This result is then plotted at the excitation frequency relative to the fundamental.

5 LEVEL DEPENDENT DISTORTION

Distortion is inherently level dependent, therefore, it is quite interesting to see how the distortion characteristics of the device under test change with level. Very often in audio magazines and published specifications for loudspeakers and microphones, little information is given with respect to maximum level output or input. For loudspeakers in particular, it is useful to know at what output level does the loudspeaker start to compress the input signal. Compression occurs when an increase in the input level does not result in a corresponding increase at the output (e.g. +3 dB input at 1 kHz results in only +2 dB output at 1 kHz). The missing 1 dB at 1 kHz can show up at other frequencies as distortion.

In Fig. 11, an amplitude sweep was performed on the same loudspeaker at a fixed frequency of 100 Hz in 2 dB steps. The top curve shows the fundamental linear response of the loudspeaker versus level and the bottom curve shows the total distortion (2nd and 3rd harmonic power summed) as a function of level. Ideally, the fundamental curve should be a straight line with a constant slope of 1. But once its maximum output level is approached, the curve starts to flatten indicating compression. Correspondingly, the total distortion curve increases, indicating that the added energy at the input is resulting in added distortion.

This is an extremely good test of how a device handles peak power conditions. Music typically contains a lot of transients which demand peak power that can easily saturate audio components. Therefore, it is interesting to see how gracefully a device approaches overload and recovers after saturating. It may be necessary to use short tone bursts in order not to damage the device, as Don Keele does in his loudspeaker reviews for Audio Magazine [2]. A more thorough description of this technique is described in my previous paper [1].

Ultimately, it would be useful and highly informative to know the distortion level across the entire audio frequency and dynamic range. In addition, distortion graphs should show individual distortion orders versus level, e.g. 2nd and 3rd harmonic. This is important for two reasons: The distortion causing mechanisms in an audio device for odd and even order distortion are different and thus behave differently with respect to level and frequency. They are also perceived differently, psychoacoustically, and therefore should be isolated [1]. Graphs of Total Distortion (e.g. THD), are dominated by the highest distortion component, usually the 2nd or 3rd harmonic. By lumping all the distortion components together, critical information can be lost.

As can be seen in Fig. 12a, the shape of the 2nd harmonic response changes dramatically at 114 dB SPL. The loudspeaker was allowed to "cool off" for 30 seconds before measuring at the next level. So it would seem that the loudspeaker's asymmetric distortion, since it is the 2nd harmonic, increases proportionally with the input across the entire audio range. In particular, the frequency range around the crossover frequency of 1 – 3 kHz, saturates first. This could be because the voltage rating for the electrolytic capacitor used in the crossover, is exceeded. Fig. 12b has the same trend at the crossover frequency, but not nearly as severe as for the 2nd harmonic. The 3rd harmonic, symmetrical distortion, is particularly sensitive to an increase in level at low frequencies. In fact, in the region of 50 - 150 Hz, an increase in the input level of 6 dB causes an equivalent increase in the 3rd harmonic distortion level of approximately 6 dB. The loudspeaker has already reached saturation at an output level of 90 dB at these frequencies. This can be seen in Fig. 11 where the slope of the fundamental starts to change. Also, note how the high frequency region of 6 – 10 kHz reaches saturation at 114 dB SPL.

6 CONCLUSION

Distortion measurements and graphs need not be difficult to make or interpret. It helps to keep in mind that distortion is a relative measurement and is therefore more easily viewed on a relative scale referenced to the fundamental. By amplitude normalizing the distortion responses at the actual measured frequency to the fundamental response before frequency normalizing to the excitation frequency, passband effects, amplitude irregularities, and room reflections can be removed. While this method may not conform to any convention or standard, it makes the distortion measurement a more useful diagnostic tool.

Analyzing a transducer's nonlinear performance is an excellent way of determining its maximum output level and compression limits. These are important design criterion. Since transducer distortion usually increases with excitation level, there is no need to plot distortion curves versus level on a three-dimensional graph.

7 REFERENCES

[1] S. F. Temme, *"Why and How to Measure Distortion in Electroacoustic Transducers"*, presented at the AES 11th International Conference on Audio Test and Measurement, Portland, Oregon, (1992 May 29 – 31).

[2] C. J. Struck, *"Presentation and Interpretation of Loudspeaker Measurement Results"*, presented at the AES 94th Convention – Berlin, (1993 March 16 –19).

[3] D. B. Keele, Jr., *"Thunder in the Listening Room: Subwoofer Shootout"*, Audio Magazine, Vol. 76, No. 11, (1992 November).

Fig. 1
Simplified representation of a transducer with a limited frequency range and a peak at 1 kHz. Fundamental (H_1), 2nd harmonic (H_2) and 3rd harmonic (H_3) of 20 Hz with same amplitude responses

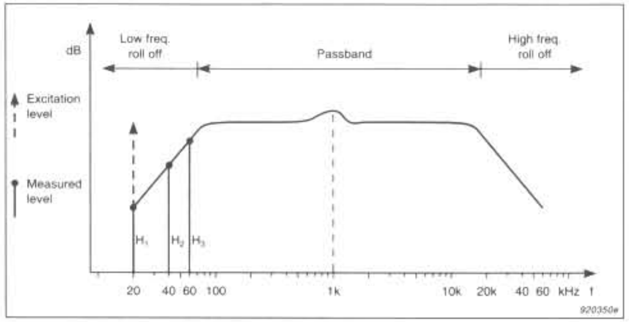


Fig. 2
Distortion curves plotted at the actual measured frequency

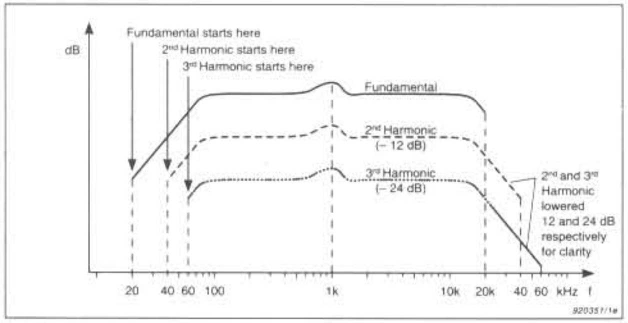


Fig. 3
Distortion curves plotted at the corresponding excitation frequency of the fundamental (frequency normalized to the fundamental)

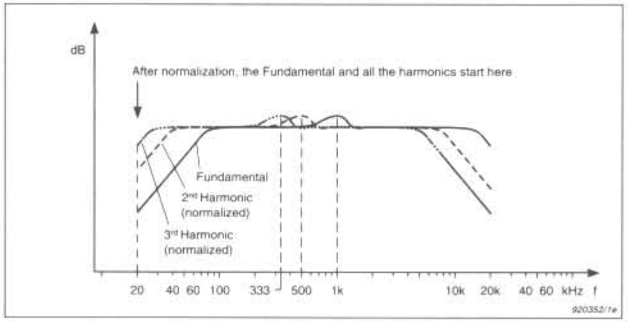


Fig. 4
Free field fundamental, 2nd harmonic, and 3rd harmonic responses of 2-way, 4 Ω loudspeaker measured at 1 m for 4 W input (sine), 1/12 octave. Harmonic responses plotted at the ***excitation frequency. (Conventional Way)***

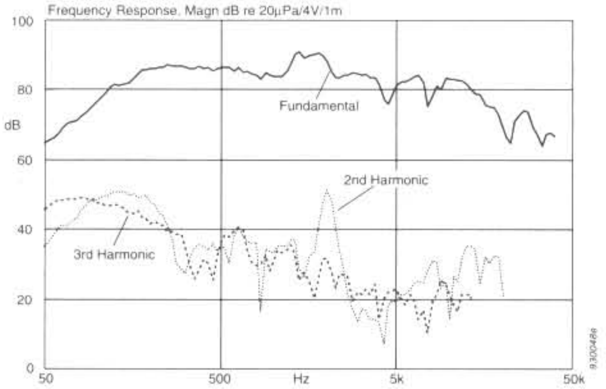


Fig. 5
Free field fundamental, 2nd harmonic, and 3rd harmonic responses of same loudspeaker plotted at the ***actual measured frequency***

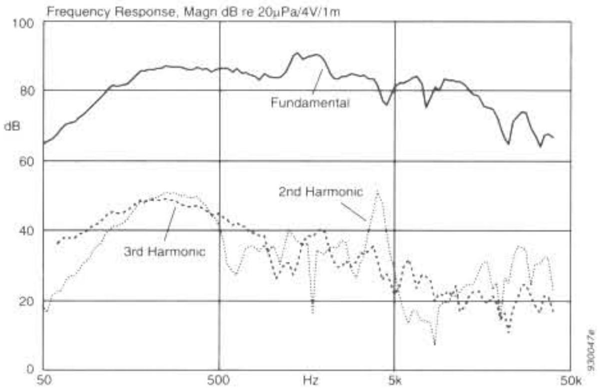


Fig. 6
2nd harmonic and 3rd harmonic responses of same loudspeaker ***amplitude normalized at the actual measured frequency*** *to the fundamental response before frequency shifting to their corresponding excitation frequency*

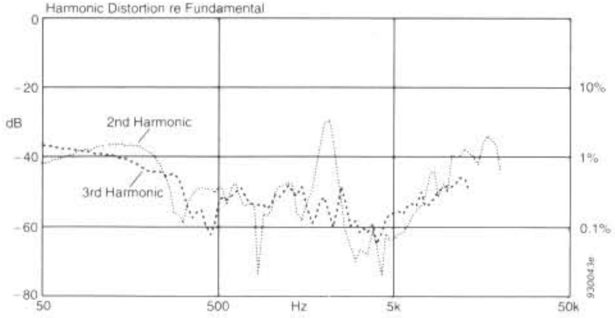


Fig. 7
2nd harmonic and 3rd harmonic response ***amplitude normalized at the excitation frequency*** *to the fundamental response.* ***(Conventional Way)***

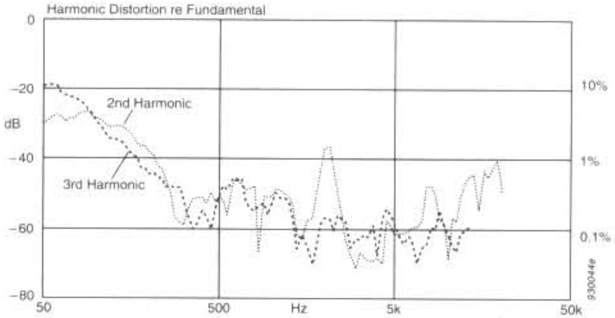


Fig. 8
Same loudspeaker measured in an ordinary room at 1 m, including room reflections. Fundamental, 2nd harmonic, and 3rd harmonic responses plotted at ***excitation frequency***

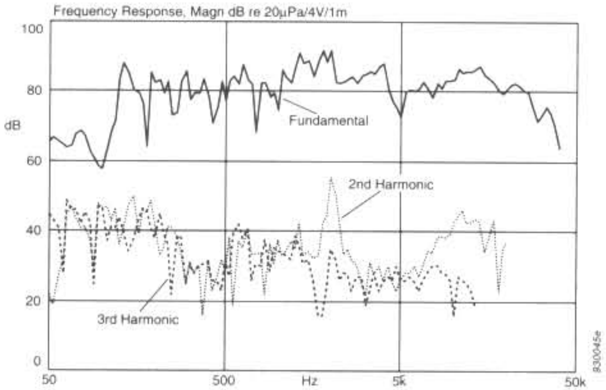
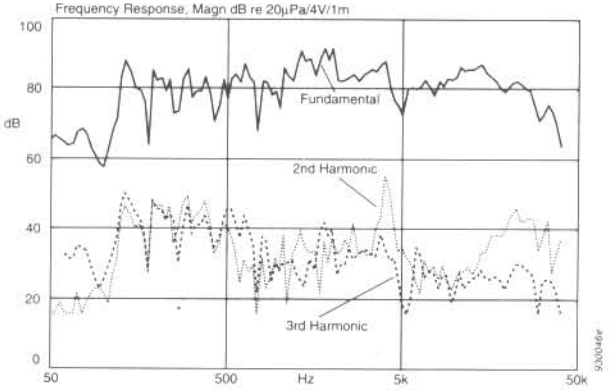


Fig. 9
2nd harmonic and 3rd harmonic responses, including room reflections, plotted at the ***actual measured frequency***



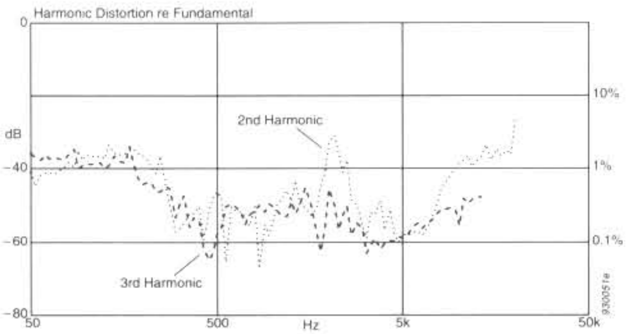


Fig. 10
2nd harmonic and 3rd harmonic responses ***amplitude normalized at the actual measured frequency*** *to the fundamental response before frequency normalizing. Room reflections essentially disappear*

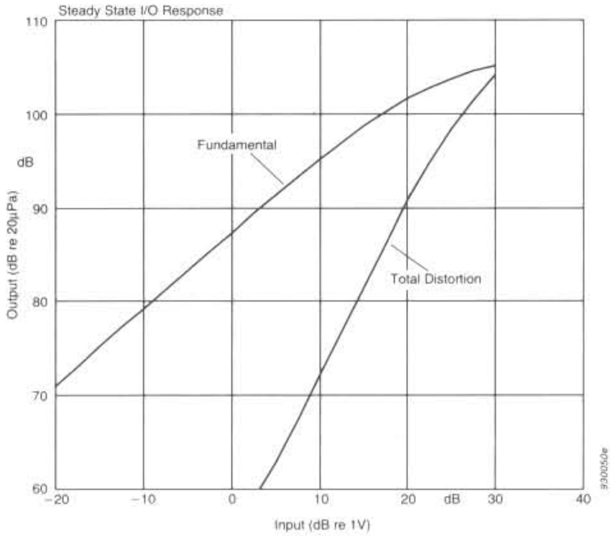


Fig. 11
Input/Output characteristics of same loudspeaker at 100 Hz. SPL at 1 m for excitation in 2 dB steps from –20 to 30 dBV. Note compression

Fig. 12
2nd harmonic (upper graph) and 3rd harmonic (lower graph) distortion of same loudspeaker, as a function of frequency and level. 6 dB steps from 90 to 114 dB SPL at 1 meter, 1/3 octave