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Audibility of Linear Distortion with Variations in Sound Pressure Level and Group Delay

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ABSTRACT

Recent psychoacoustic studies of nonlinear distortion have yielded some new insights into what audible problems in loudspeaker might be related to. This paper will show the results of recent subjective tests which extend the work of various previous works to show that sound level significantly affects the perception of linear distortion in audio systems. This means that the hearing system itself is nonlinear and what has been thought of as being nonlinear distortion in the audio system may actually be a nonlinear perception directly in the receiver itself.

1. INTRODUCTION

Recent studies of the perception of nonlinear distortion by Geddes and Lee [1], Lee and Geddes [2], and Geddes, Lee and Magalotti [3] have indicated that current popular beliefs on the perception of nonlinear distortion is misleading. Lee and Geddes [2] demonstrated that the perception of nonlinear distortion does not correlate with the commonly used metrics of THD and IMD, but that it does correlate with a new metric. This new metric is based on the shape of the nonlinear transfer function of the underlying system, instead of the traditional method of relying on the spectral changes. This new approach, while more complex to implement than the conventional THD or IMD, has shown to be effective in predicting the audibility of nonlinear distortion. In brief, this new metric predicts that the higher the order of the nonlinearity, the more likely it is to be audible. While this idea is not new, it has NOT been previously demonstrated to be effective until recently by Lee and Geddes [2].

In regards to the loudspeakers application, the research reported by Lee and Geddes has significant implications. Loudspeakers do not ordinarily have high orders of nonlinearity because they are mechanical devices - higher orders of nonlinearity require large rapidly changing forces. This phenomenon is not uncommon in electronics, but it is atypical in most mechanical devices. Most loudspeakers are high in second and third order nonlinearities, which, for the most part, were found to be benign. However, orders above these will be uncommon in a properly designed mechanical system like a loudspeaker. Adding to this situation are the results from [3] where it was found that even very high levels of nonlinear distortion in a compression driver (as measured by THD) were completely inaudible to the subjects; a result which was not at all intuitive nor expected.

Contrary to the above situation is that there is little doubt that compression drivers on horns exhibit a sound characteristic that is usually described as nonlinear distortion. The sound quality decreases as the sound level increases indicating some form of nonlinearity. This is normally attributed to the known nonlinear nature of sound within a horn. However, once again recent work [1, 2] calls this assumption into question. A horn will seldom exhibit anything above a 2^{nd} order nonlinearity, although this order can migrate upward to higher orders in a long horn, although this later situation is not usually found in practice.

Recent investigations into a different type of waveguide design by Geddes [4] and subsequent subjective testing has indicated that there might be an alternative explanation as to why this particular system (the horn/driver system) could exhibit the known subjective effect of lower sound quality at higher levels while being consistent with the recent work indicating that it is not nonlinear distortion that one is hearing.

By minimizing internal reflections and diffraction within the horn/waveguide, it was found that the typical horn sound quality was no longer apparent and that these devices did not exhibit an increasing loss of quality with sound level. It is important to note that these effects (reflections and diffraction) are linear phenomena, not non-linear ones. The question now is: what is the mechanism that could cause the commonly observed results for these devices at higher levels and yet be consistent with the recent test results on nonlinear distortion.

Several reports by Toole et. al. [5, 6] have indicated that listeners could perceive lower amounts of added linear distortion if this distortion were delayed in time. More recently Moore [7] has described how group delay could be audible (although he concludes that group delay would not typically be audible in setups such as the one used in his study) and, most importantly, that the audibility of group delay is dependent on the absolute playback level. This last piece of information is of paramount importance to this study, although it is only casually observed in Moore’s work.

A reasonable hypothesis to this situation might be that it is in fact the perception of the sound distortions – the linear ones - and more specifically the group delay of the reflections and diffraction, that is actually nonlinear. If this is true, then the system itself – the loudspeaker in this specific example – need not be nonlinear at all in order for its sound quality to worsen at higher playback levels or on higher level passages of music.

This hypothesis has profound implications which warrant a further investigation into its validity. This report is a first step in this direction - a fundamental study into the perception of diffraction/reflection types of linear distortion as a function of three variables, the level of the distortion, the delay of the distortion and the absolute playback level of the sound.

2. METHOD

A short musical passage was recorded directly from the original compact disc as a wave file, referred to here on as the source. The material chosen was a 10 second excerpt from Crossroad by Tracy Chapman. Seventy-two different stimuli were then digitally simulated from the reference source using MathCad to represent an array of distortions. These seventy-two stimuli are composed from three independent variables, namely the linear distortion level, the delay time and the absolute playback level. Different step sizes were used in each independent variable to examine the main effects and interactions.

First, the linear distortions were generated by utilizing a high-pass filter with a cutoff frequency at 2kHz, and added back into the reference to yield shelving levels at 2, 4 and 6 dB. A spectral example of the 4 dB filter is shown in Fig. (1). Second, there were six delay times varying from 0-1ms (0, .2, .4, .6, .8 & 1.0). An example of the filter for a 4 dB shelf with a .4 ms. delay is shown in Fig. (2). Lastly, there were four playback levels (71, 74, 77 and 80 dB SPL). In total, a matrix of 72 stimuli (3 x 6 x 4) was generated. In addition, four reference stimuli (unmodified files) were used to track the subjects' ability to distinguish true modifications from nonexistent ones. Hence, each trial consisted of a total of 76 stimuli. All stimuli were normalized based on their overall rms level to the correct playback level for those stimuli. In other words, it is one of the four playback levels. The playback level was calibrated using a noise signal at the maximum rms level through the insert headphones and into a Zwislocki coupler, and measured by a B&K Sound Level Meter. The volume setting on the playback equipment was adjusted to set this level at 80 dB SPL. Thus the level for these tests was the absolute SPL level in the ear canal. This makes these levels significantly louder when compared to a normal room SPL level measurement.

In total thirty-four listeners with normal hearing sensitivity participated in this study. Each listener was instructed to compare each of the 76 stimuli with a reference stimulus that had an equivalent rms level. Each listener rated the audibility of the differences between the test stimulus and the reference on a 10-point likert scale. The 76 stimuli were randomly presented within a trial, and each listener completed three trials. Listeners were paid for their participation.

The stimuli were presented via the Etymotic ER-4 MicroPro insert earphones. These earphones are designed to give the most accurate response with normal commercial recordings. They were chosen for their low distortion, natural sound character and common usage in acoustical subjective testing.

3. RESULT

A 3x6x4 GLM repeated measures analysis was administered. The results indicated significant main effects for all three factors - linear distortion level ($p < .001$), delay time ($p = .03$) and playback level ($p < .001$). Interaction effects were observed with linear distortion level and delay ($p=.005$) and distortion with playback level ($p =.04$).

Fig. (3) displays the results of the main effect playback level at the various delay times for a 2 dB linear distortion level. The heavy line is the mean value across the delays for a given playback level. Based on an assessment of the data for the reference stimuli compared to itself, a threshold of reliable detection for this group of subjects is estimated to be about .2. For ratings below this level, the average subject could well be guessing. With this assumption it can be noted that the 2 dB linear distortion level was probably not reliably detected by the subjects. This implied that some listeners could do this task, but not all.

Fig(4) shows the same variables as Fig.(3) but for a linear distortion level of 4 dB. The results are both reliable and significant. A clear effect of increasing audibility with both playback level and delay is evident

Fig.(5) shows the data for a 6 dB linear distortion level. The same trend is evident as in Fig.(4), but at a higher rating level showing that the 6 dB linear distortion level was more audible than the 4 dB level.

Fig.(6) shows the data for a 4 dB linear distortion level, although the ratings are shown versus delay time with playback level as a parameter. This is the same data as shown in Fig.(4), but plotted differently.

Fig.(7) is the same data as Fig.(5) except that the data is shown with delay time as the X-axis.

4. CONCLUSION

The results of this study indicated that within the constraints of this simple study that the perception of linear distortion is dependent on the level and the delay time of the linear distortion and the playback level. The first two main effects were known as indicated in the background discussion.. However, while it may seem intuitively obvious, the significant increase in the audibility of linear distortion has not been shown before. Further, that this audibility of linear distortion increase with both playback level and with delay time is extremely important.

These results mean that a subjective impression obtained where playback level was not controlled is of questionable validity.

The combined effects of playback level and delay have strong implications to the perceived perception of nonlinear distortion. It is not possible to say, without complicated objective tests, if what is being perceived is a nonlinearity in the system or a nonlinearity in the subjective perception as described in this paper. This has profound implications to the subjective evaluation of nonlinear distortion in audio systems most particularly loudspeakers where the delay factor can be quite strong.

Time delayed resonances, nearby cabinet reflections and edge diffraction, waves in horns; all have delay times on the same order as this study. A loudspeaker that is evaluated at 70–80 dB (SPL) may have a very different perception at 90-100 dB even if it is completely linear.

A THD distortion curve will not reveal this effect, nor will a frequency response graph. A careful look at the impulse response might yield the best insight, however this has not been quantified. Methods for measuring the nonlinear effects of our subjective perception are currently under investigation.

Another point is that the usefulness of a loudspeaker for audio playback can have a sound power output limit that is independent of its electrical power handling or its nonlinear distortion characteristics. Loudspeaker evaluations that take place at a fixed level, are seriously inadequate at revealing the true quality of these systems.

5. REFERENCES

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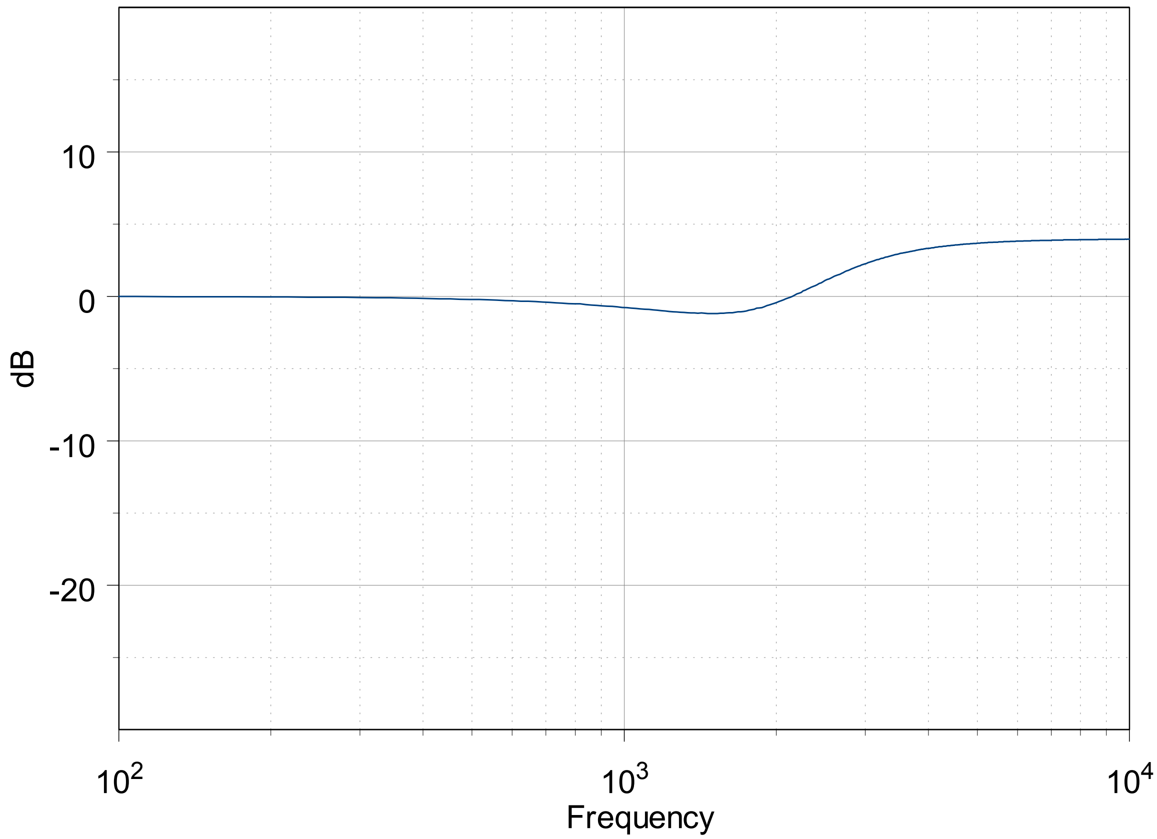

Figure 1 - Filter response for zero delay + 4 dB stimulus

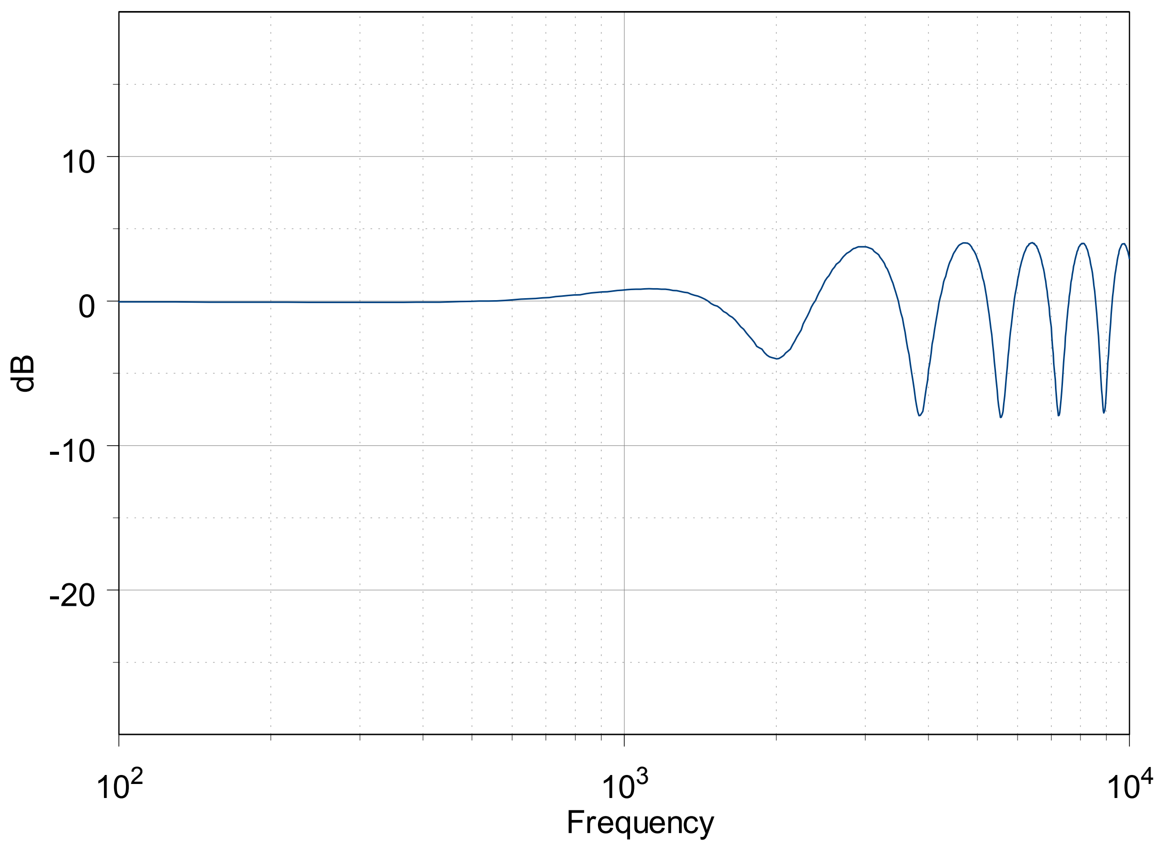

Figure 2 - Filter response for delay = .6 ms, + 4 dB stimulus.

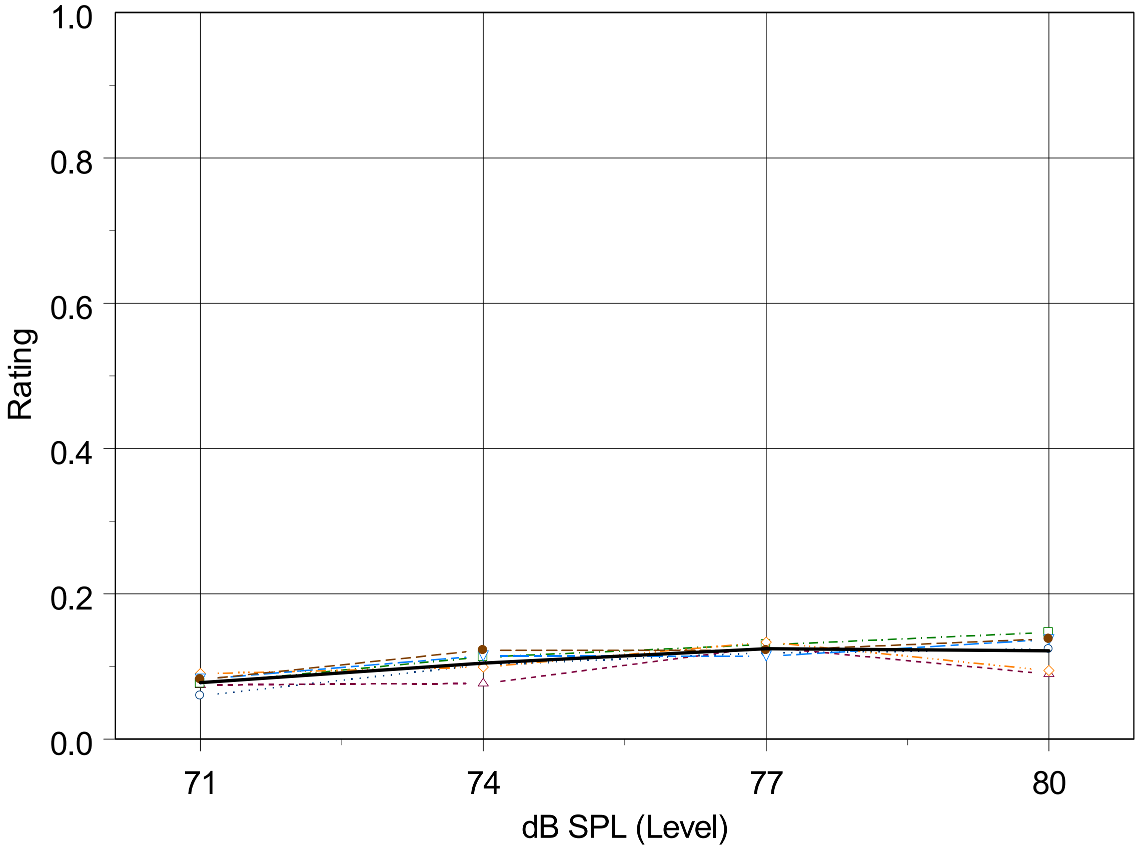

Figure 3 – Ratings versus playback level for +2 dB linear distortion with delay as a parameter. These data are not significant.

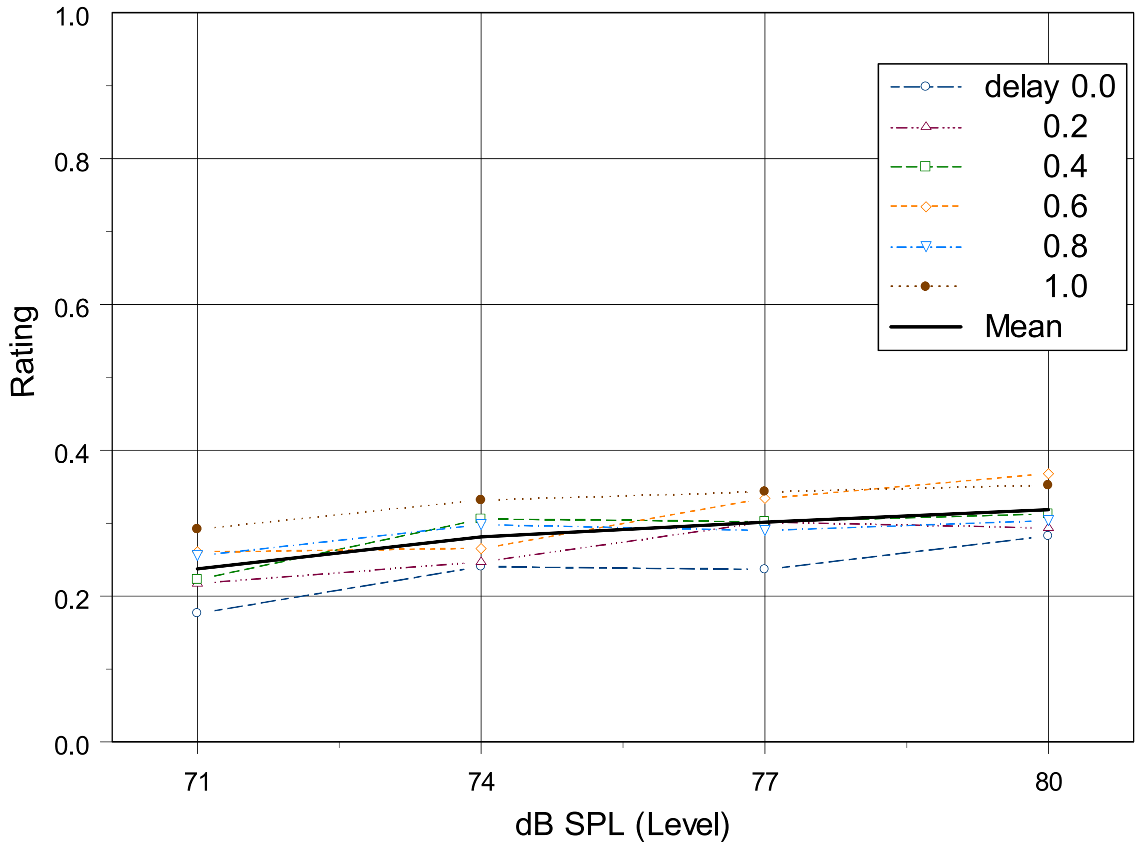

Figure 4 - Ratings versus playback level for +4 dB linear distortion with delay as a parameter. These data are significant at .05.

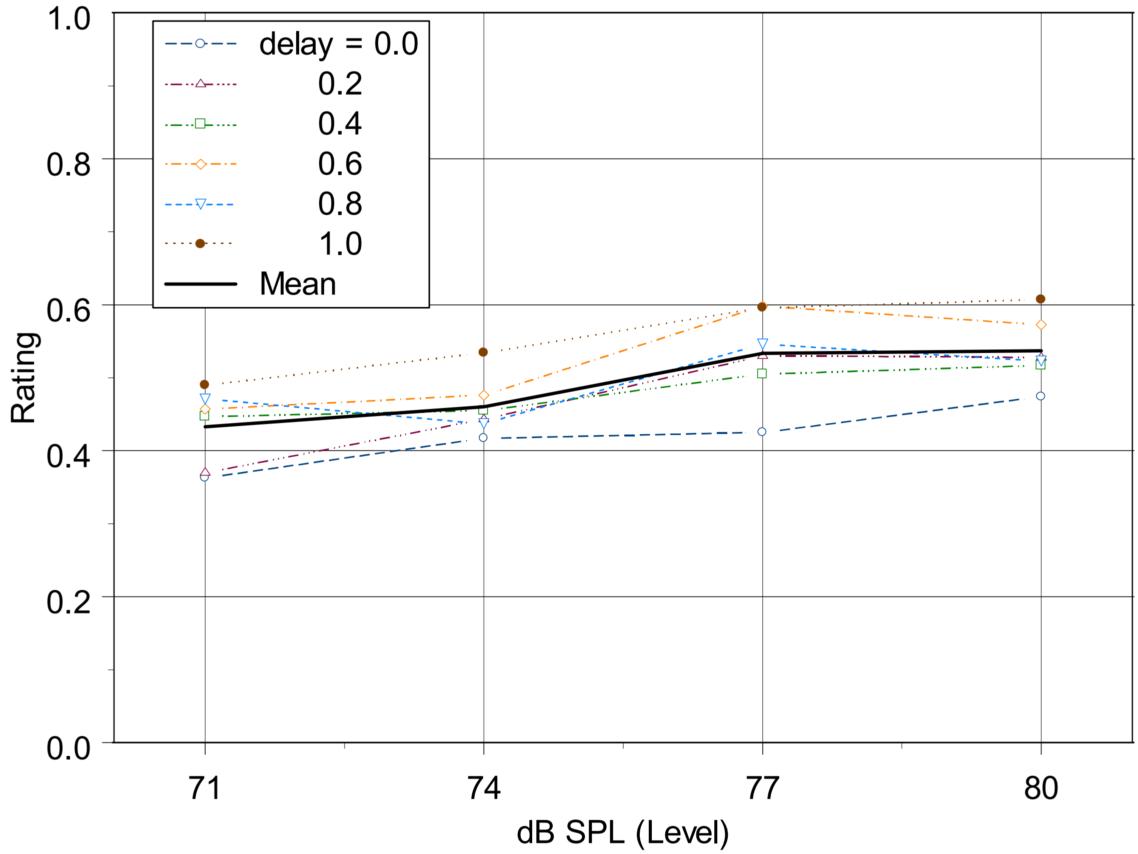

Figure 5 - Ratings versus playback level for +6 dB linear distortion with delay as a parameter. These ratings are significant at .005.

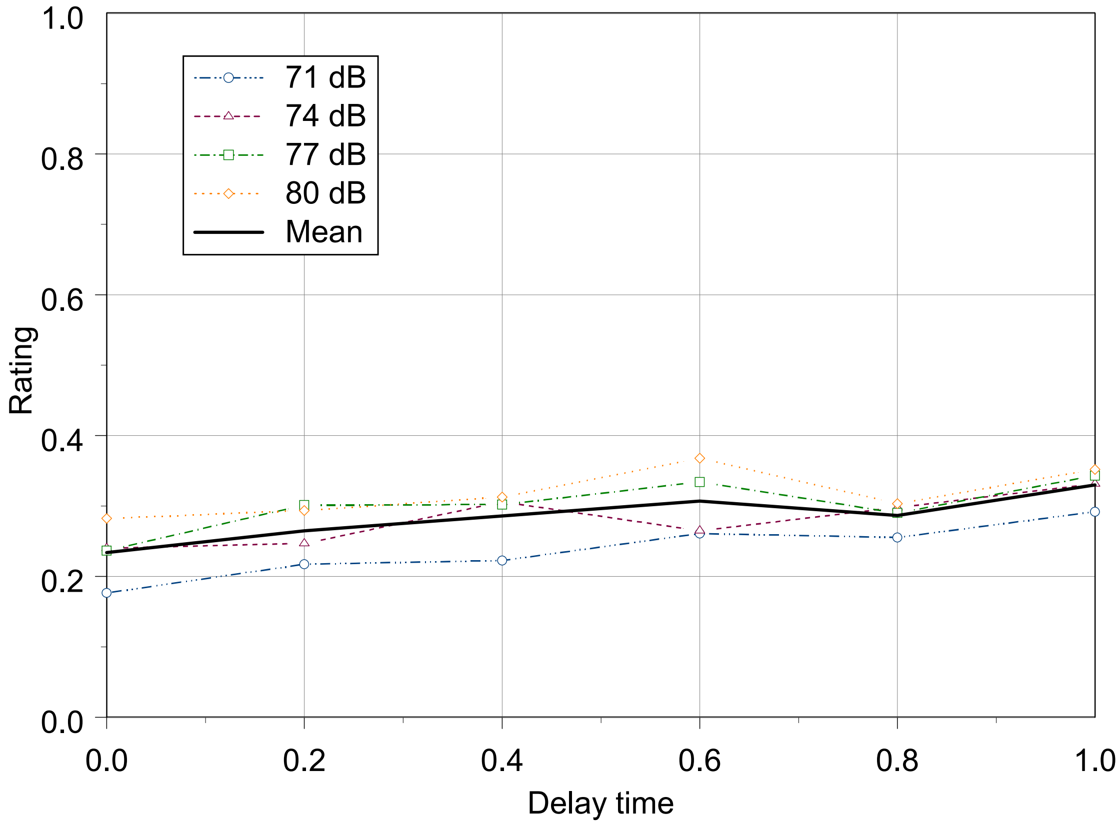

Figure 6 - Ratings versus delay for +4 dB linear distortion with playback level as a parameter.

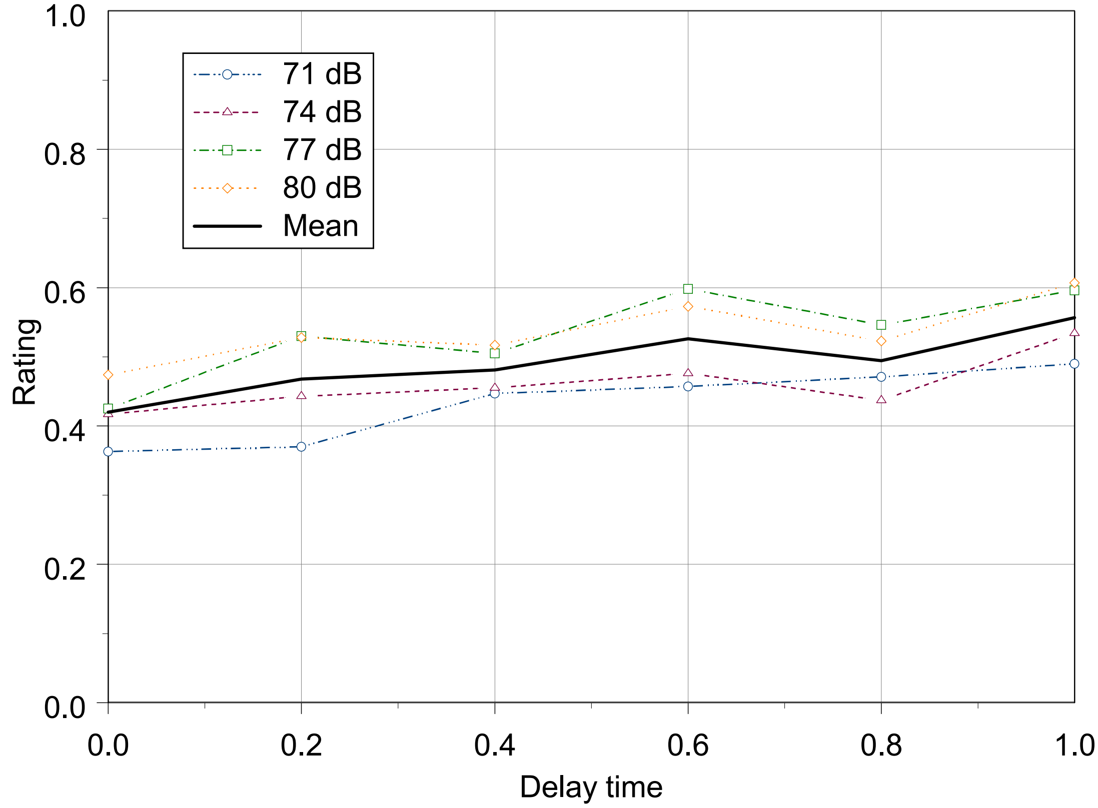

Figure 7 - Ratings versus delay for +4 dB linear distortion with playback level as a parameter.