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Loose Particle Detection in Loudspeakers

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ABSTRACT

During the loudspeaker manufacturing process, particles may become trapped inside the loudspeaker, resulting in a distinctive defect that is easily heard but difficult to measure. To give a clearer view of the problem, Time-Frequency maps are shown for some defective loudspeakers. Based on this analysis, a reliable testing procedure using a swept-sine stimulus, high-pass filter, and RMS-envelope analysis is presented. Further possible enhancements and applications of the method are listed.

1. INTRODUCTION

During the loudspeaker manufacturing process, particles of dirt, solder beads, glue, magnet or metal chips can become lodged in the speaker voice coil vicinity or trapped beneath the dust cap. When the speaker is driven under certain conditions, these particles may hit randomly, producing a distinctive rattling sound which is easily heard but surprisingly difficult to detect by traditional computer-based tests using frequency analysis.

In recorded data, the fault appears as impulsive noises added on the stimulus wave [Figure 1-1]. These impulses are not related to the frequency of the stimulus, but rather to the displacement amplitude of the diaphragm. The loose particle problem is much more noticeable and occurs more often when the speaker is driven near or below its resonant frequency, when the displacement of the diaphragm is the greatest.

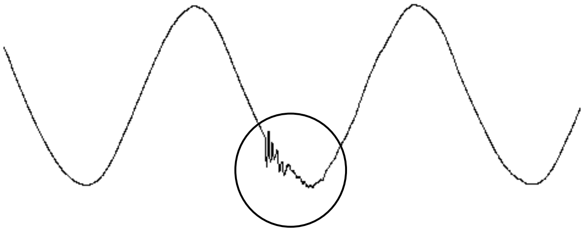

Figure 1-1: Detail of recorded time signal of a loudspeaker with a "Loose Particle" defect

Regardless of the excitation frequency, these impulses occur at random times, uncorrelated to the stimulus signal's harmonic content. Tests that rely primarily on harmonic analysis are well suited to detect repetitive faults [Ref.1] but cannot reliably determine the presence of non-periodic faults such as loose particles. The figures below show the harmonic analysis of a "good" speaker versus a speaker with a loose particle defect.

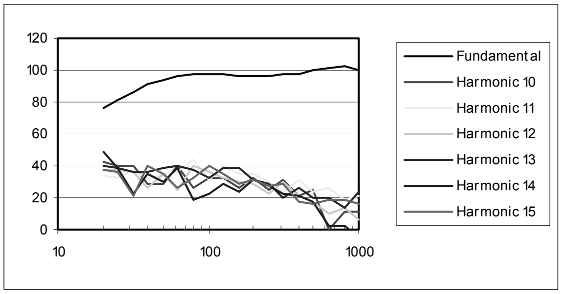

Figure 1-2:"Good" Speaker: Fundamental and Harmonics

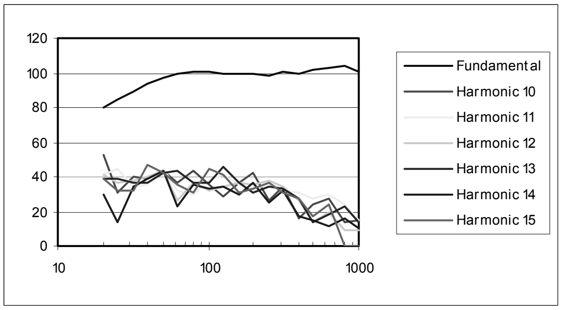

Figure 1-3: "Loose Particle" Speaker: Fundamental and Harmonics

From this analysis, the loose particle fault is not obvious (See Appendix 8.1 and 8.3 for further analysis of the same data set). It is clear that a new testing method is needed to detect non-periodic faults quickly and accurately.

This paper deals with the application of time-frequency analysis to determine the unique characteristics of the "loose particle" fault. The information discovered through this analysis led to the development of a relatively simple process to detect the fault. This process is explained in detail.

2. TIME-FREQUENCY ANALYSIS

2.1. Obvious Cases

In order to determine the unique characteristics of the loose particle fault, several loudspeakers with varying faults were tested with a swept-sine stimulus over the frequency range of 20 - 1000 Hz. This frequency range was chosen because loose particles tend to occur near the resonant frequency of the speaker, which in this case was around 57 Hz (See Appendix 8.5). Using proprietary software, data was collected and time-frequency analysis performed using a Short-Term Fourier Transform to produce the figures below.

In a speaker with no loose particle fault [Figure 2-1], the time-frequency map shows only the stimulus signal and a few additional harmonics.

In a speaker with a rub & buzz fault but no loose particles, the rub & buzz fault can be seen as clusters of harmonics "smeared" along the time axis [Figure 2-2]. The rub & buzz fault is recognized as a periodic disturbance.

In a speaker with an obvious loose particle fault, the loose particles hit randomly in time, and appear "smeared" along the frequency axis [Figure 2-3].

The map for the speaker with both faults clearly shows the difference between the rub & buzz and loose particle faults. There are loose particle "streaks" over a wide range of frequencies but a short span of time and rub & buzz "streaks" running in narrow frequency bands over longer periods of time [Figure 2-4].

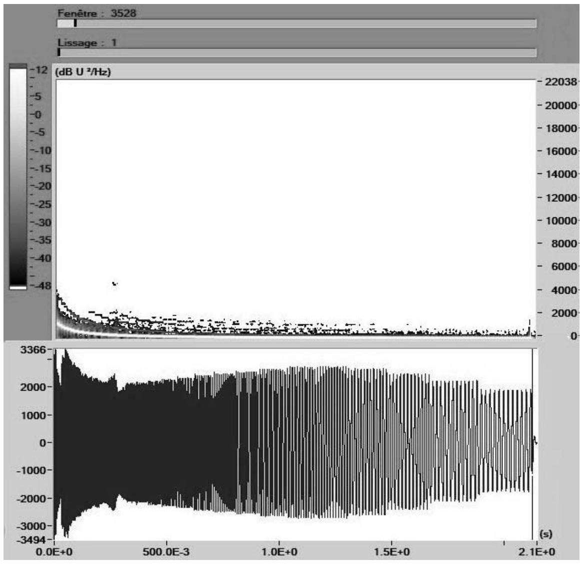

Figure 2-1: Good Speaker

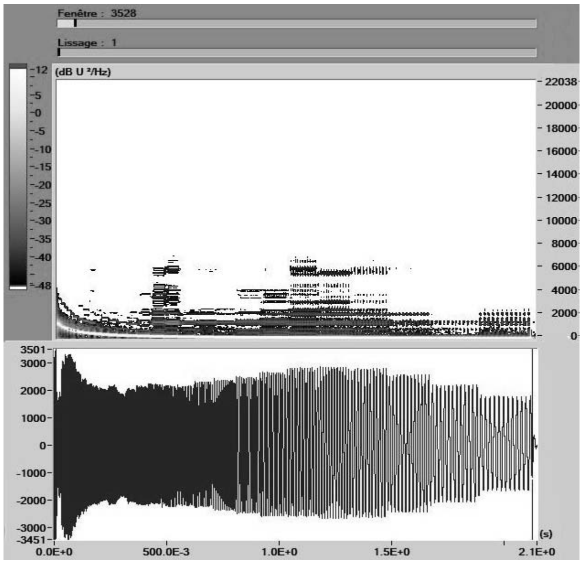

Figure 2-2: Rub & Buzz defect

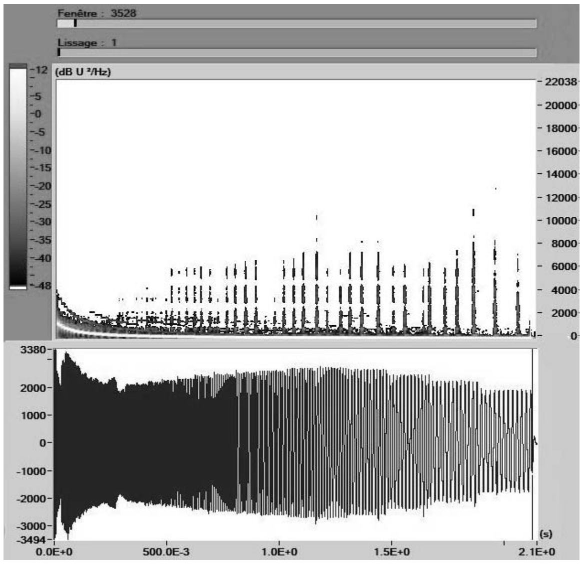

Figure 2-3: Loose Particle defect

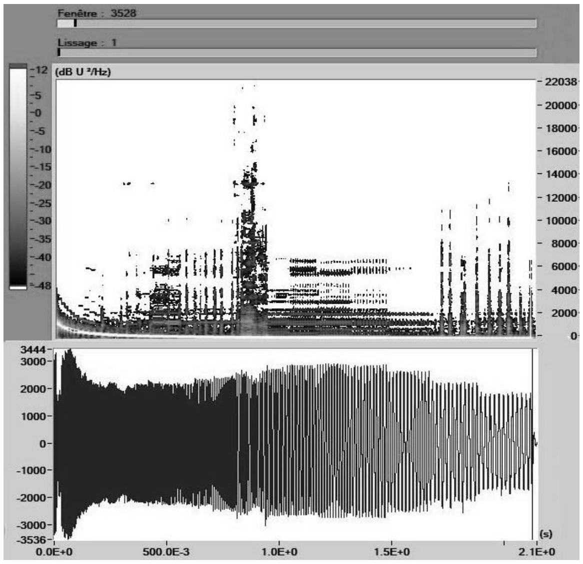

Figure 2-4: Rub & Buzz and Loose Particles

Note: All Figures above use the same window settings and graph scale. The X Axis is time from 0 to 2.1 seconds, the Y Axis is a linear frequency scale from 0 – 22038 Hz, and the Z Axis is energy spectrum density in dB as a grayscale.

2.2. Borderline Case

While the figures above demonstrate the differences between obvious rub & buzz and loose particle faults, how sensitive is this method at finding subtle differences in the amount of loose particle fault in borderline cases? To examine a borderline case, a speaker with a barely audible loose particle fault was tested. The speaker tested was useful because the defect could be controlled: when positioned facing up the particle would become lodged and the speaker would perform normally, but when positioned facing down, the particle would become loose and cause a slight disturbance.

Note: The energy spectrum density is shown over a larger dynamic range than in the previous figures, as needed to demonstrate the fault effectively. As such, more ambient noise appears on the graph.

When the particle becomes lodged, the time-frequency map shows only the stimulus sweep and a minimum of ambient noise, with no other outstanding artifacts [Figure 2-5]. Even when barely audible, the fault is apparent on the time-frequency map. [Figure 2-6]

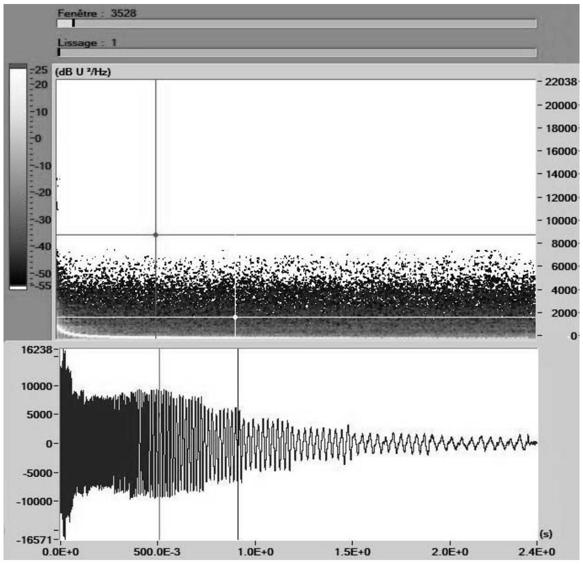

Figure 2-5: No Loose Particles

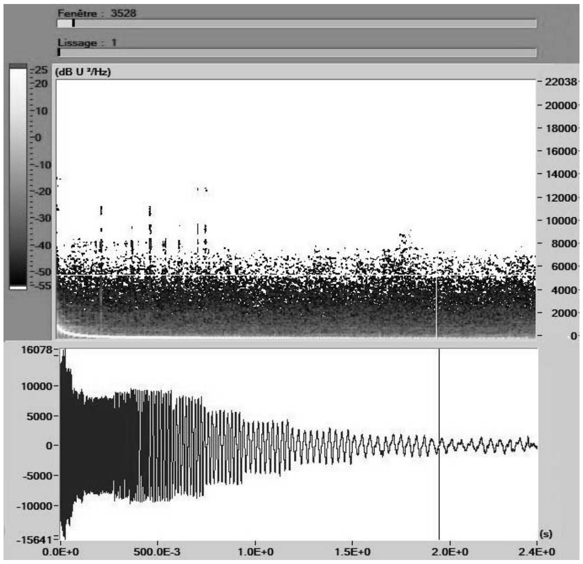

Figure 2-6: Borderline Loose Particle case

Although the fault in Figure 2-6 can be easily identified by a visual check, harmonic analysis fails to show much difference between these cases (See R&B curves, Appendix Figure 8.1-3 & Figure 8.2-3). The problem still remains how to test for the loose particle fault quickly, automatically, and produce reliable results. In the following section a new and successful method is presented to solve this problem.

3. METHOD

3.1. Time versus Frequency

Frequency analysis is well suited for studying periodic signals, like steady waves or repetitive events. It gives the frequency of repetition and the harmonics. This is the case for rub & buzz where repetitive hit defects show up in the spectrum as a strong harmonic pattern. That can be clearly seen in Figure 2-2.

In the case of randomly spaced impulses, the spectrum becomes a broadband random noise with no distinctive pattern. Frequency analysis is not particularly revealing for this type of signal.

Loose particles are usually randomly spaced impulses so far apart that they are heard as distinct events from each other (see Figure 2-3). Moreover, they have a broadband spectrum, which is not of primary interest. Therefore, time analysis is better suited for detecting these distinct events.

3.2. Time Envelope Detection

Time Envelope analysis has been successfully used for detecting faulty bearings in the machine industry [Ref. 2].

Defects in bearings such as cracks on races or spallings on balls produce repetitive impacts. The bearing cage acts like a bell. Each pulse excites the resonant frequency of the cage. In most cases, the rolling noise is concentrated in the low frequencies well below the frequency range of the pulses.

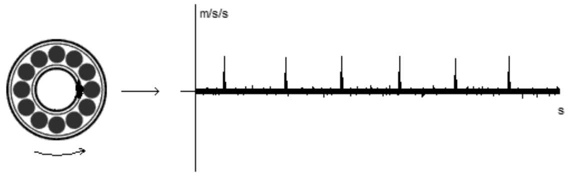

Figure 3-1: A crack in the inner race of a bearing produces a repetitive impact when the balls roll over it

The detection method most commonly used for such a defect is:

1. Band-pass filtering of the signal around the resonance frequency of the cage
2. Envelope extraction (by running RMS or Hilbert transform)
3. Threshold detection (Pass/Failed test)
4. Frequency analysis to determine the repetition rate of the pulses and find out the location of the defect (inner race, outer race, or ball)

This method has been applied with good results for maintenance purposes in the machine industry for over 20 years.

3.3. Loose-Particle Detection Method

3.3.1. Choice of the Method

A good detection method must be simple, reliable, and fast. To be reliable, the difference between bad and good loudspeakers must be enhanced as much as possible.

In this method, a swept-sine is used around and below the resonant frequency of the loudspeaker as a stimulus to shake the loose particles and reveal the defect. By doing this, the signal remains in the lower frequencies and the loose particle impulses spread clearly in the upper frequencies. Just like faulty bearing detection, it is necessary to detect impulsive noises added to a low frequency signal. The case is even simpler because the “good” signal is narrow band and the background noise can be expected to be low in level. So it was decided to apply a detection method similar to the faulty bearing detection method.

3.3.2. High-pass filtering

Using a high-pass filter, the sine stimulus signal is removed. This reduces and simplifies the problem allowing discrimination between a train of pulses for bad speakers and background noise for good speakers.

A Bessel recursive filter is selected because it has the shortest impulse response. Therefore, the loose particles impacts are less spread out and remain high. A recursive filter is chosen rather than a non-recursive FIR filter because it is much faster and phase linearity is not relevant in this case. A fourth order filter is selected, which provides a slope of 80 dB/decade in the attenuation band. To attenuate the sine stimulus by 80 dB, the cutoff frequency is chosen equal to 10 times the sine frequency. In the case of a stepped sine or swept sine stimulus, the cutoff frequency F_c is set according to the maximum stimulus frequency F_{max}.

Note: the requirement is $F_c = 10F_{\max} < \frac{F_s}{4}$,

where F_s = sampling frequency.

This ensures that half of the available bandwidth is kept for detection purposes. With a sampling frequency of 44,100 Hz, F_{max} must stay below 1103 Hz. This is consistent with the loose particles defect appearing for low stimulus frequencies only.

3.3.3. RMS Envelope Calculus

After filtering, an alternating signal remains. In order to detect the peaks of acoustic energy due to the loose particles, the RMS envelope of the signal must be calculated. One method is to use the Hilbert transform. That method, however, involves substantial calculus. So a running RMS integration was selected:

1. Square the filtered signal to get instantaneous power
2. Obtain the power envelope by an exponential running average
3. Square root the power envelope to get the RMS envelope

To perform an exponential running average, a low-pass 1st order filter (RC-filter) is selected. Again, a recursive filter is chosen for its speed.

The mathematical definition of the exponential RMS envelope used is:

$$\mathrm{x}_{\mathrm{rms}}(\mathrm{t})=\sqrt{\frac{2}{T_A}\int_{-\infty}^{t}\mathrm{x}^2(\tau)\cdot e^{2(\tau-t)/T_A}d\tau}\ ,$$

where x(t) is the high-passed filtered time signal. The averaging time T_A is set according to F_c.

3.3.4. Threshold Detection and Peak Count

The final step is to detect valid peaks in the RMS envelope. The valid peaks are those above a certain threshold for a duration greater than T_A, the RMS averaging time. The user must set the threshold high enough so no peaks are detected for good speakers, but low enough to detect peaks for bad speakers. Establishing the threshold level requires some trial and error.

The peaks are then counted. The number of peaks can discriminate real from false events. For example, in an anechoic chamber, a speaker can be said to fail the test if even one peak is found, but in a noisy environment, such as a factory, the peak count limit should be set higher to reject false events caused by foreign impulsive noises (such as a tool falling on the ground). By setting the threshold and maximum number of peaks appropriately, the test can give meaningful results in most test environments.

4. RESULTS OF LOOSE-PARTICLE DETECTION

4.1. Time Envelope Analysis

The SoundCheck™ measurement system was used to apply the Loose Particle Detection Method to the following loudspeakers:

- Good woofer
- Woofer with loose particles (borderline case)
- Woofer with loose particles (obvious case)
- Woofer with rub & buzz

For each of these, the following are shown:

- A graph with the envelope of the filtered time signal and the threshold of detection
- The number of loose particles impacts detected (#LP)

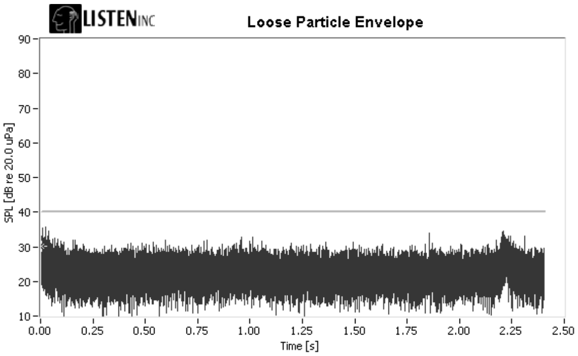

Figure 4-1: Good Woofer. #LP: 0.

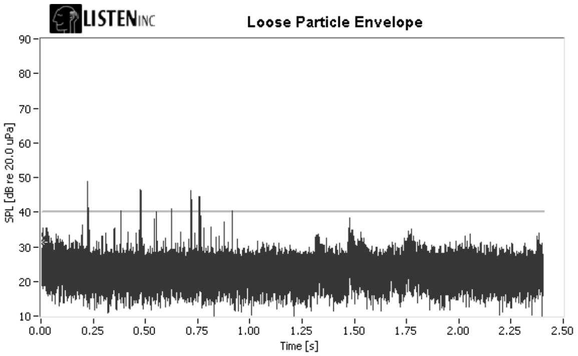

Figure 4-2: Borderline Case. #LP: 8

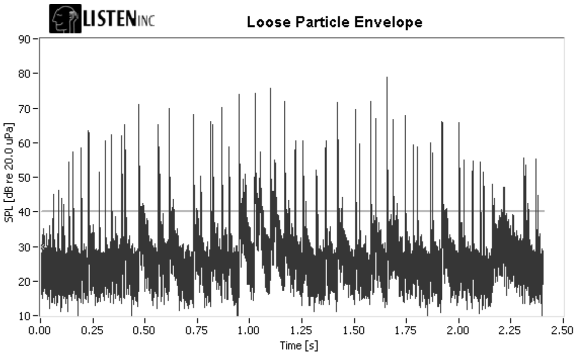

Figure 4-3: Obvious case. #LP: 290

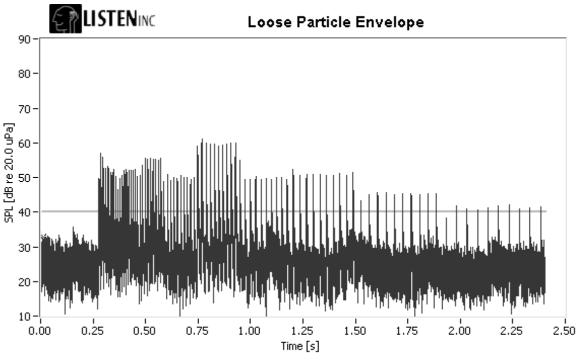

Figure 4-4: Rub & Buzz. #LP: 250

This demonstrates that the Loose Particle Detection Method yields very distinct results for the different loudspeakers. The difference between good and bad loudspeakers is clear. Further analysis of the data above can be found in the appendix.

4.2. Advantages & Limitations of the Method

Advantages:

- The method is very sensitive. In the case of the borderline speaker, the defect was almost inaudible.
- The method also detects rub & buzz very well.

Limitations:

- Because there is no frequency analysis involved, the method cannot tell the difference between loose particles and rub & buzz.
- The user must set the threshold level and the number of acceptable peaks.
- The method may be sensitive to noise, especially impulsive noises.

5. FURTHER DEVELOPMENTS

Based on this work, some potential areas of study are:

- Band-pass versus high-pass filtering: in case of noisy environment, filtering around the resonant frequency of the speakers may be useful to increase the signal/noise ratio and avoid false detection of peaks.
- Statistical analysis based on Crest factor [Ref. 3], Skew, Kurtosis, providing the “spikiness” of a signal, might be useful for further analysis.
- Frequency analysis of the RMS envelope for better fault diagnostic.
- Psychoacoustics: Psychoacoustic measurements like loudness or other ear related filters [Ref. 4] could be used to detect audible peaks in the same manner as the human ear.

6. CONCLUSION

Although the testing method devised uses basic and classical signal processing, the results obtained prove that it is reliable and efficient. This procedure can be run regardless of other distortion effects, and can detect loose particles even if they are barely audible. With proper limit settings, this test provides a fast check for the loose particle fault.

Another interesting result of this new method is that it can detect rub & buzz fairly reliably, although rub & buzz detection using high order harmonic frequency analysis gives a better signal to noise ratio and greater diagnostic capabilities. In fact, this test can detect any impulsive distortion, repetitive or not. When integrated into a full speaker test procedure, this test will be a valuable tool for any loudspeaker production line.

7. REFERENCES

[1] S.F. Temme, “Are You Shipping Defective Loudspeakers to Your Customers?” Listen, Inc. Application Note, 2000 January http://listeninc.com/index/notes/Rub&Buzz.PDF

[2] Martin Angelo, “Vibration Monitoring of Machines”, Brüel & Kjær Technical Review, No. 1, 1987

[3] W. Klippel, “Measurement Of Impulsive Distortion, Rub & Buzz, And Other Disturbances”, AES Convention Paper 5734, 2003 March

[4] F. Leonhard, “Harmoni™ Technology”, Leonhard Research Application Note, 2002 March

8. APPENDIX

8.1. Analysis of Good Speaker

This analysis corresponds to the data used in Fig 4-1

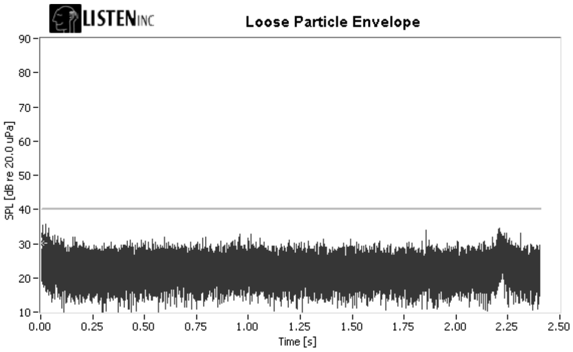

Figure 8.1-1: Time Envelope

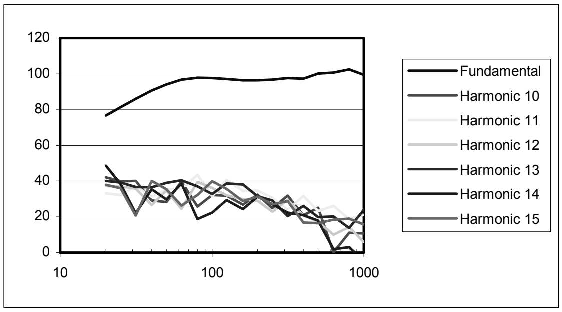

Figure 8.1-2: Harmonic Levels

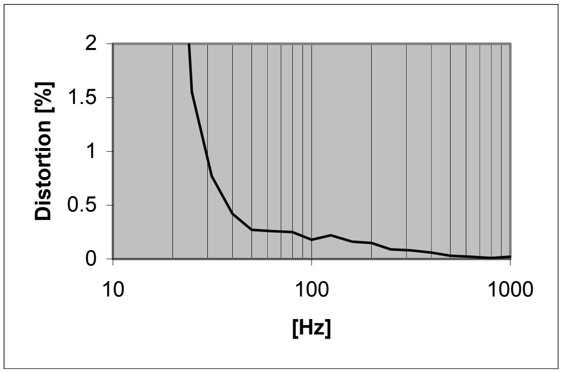

Figure 8.1-3: Rub & Buzz distortion (Based on Harmonic 10-15)

8.2. Analysis of Borderline Case

This analysis corresponds to the data used in Fig 4-2

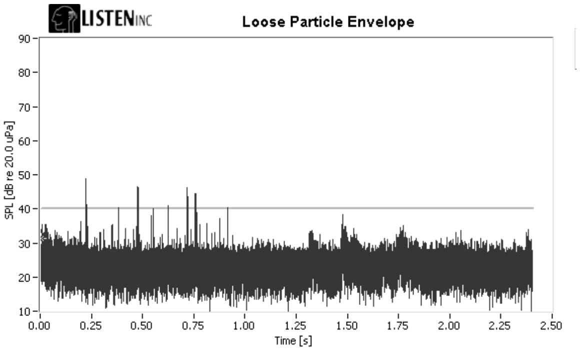

Figure 8.2-1: Time Envelope

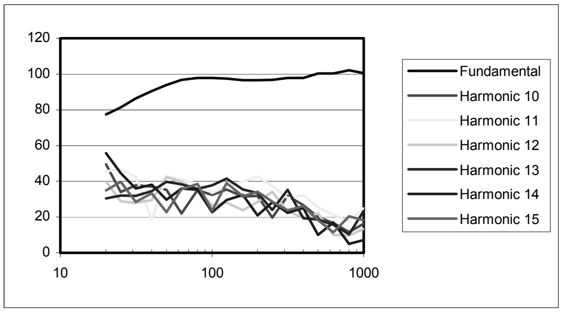

Figure 8.2-2: Harmonic Levels

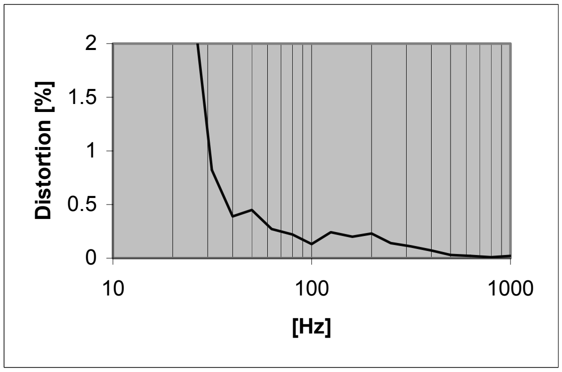

Figure 8.2-3: Rub & Buzz distortion (Based on Harmonic 10-15)

8.3. Analysis of “Loose Particle” Case

This analysis corresponds to the data used in Fig 4-3

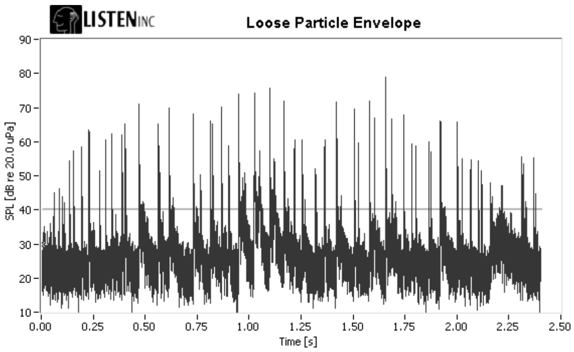

Figure 8.3-1: Time Envelope

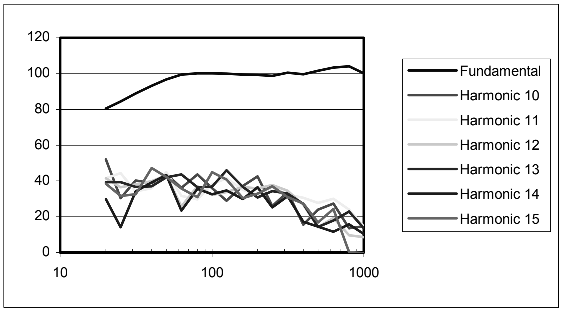

Figure 8.3-2: Harmonic Levels

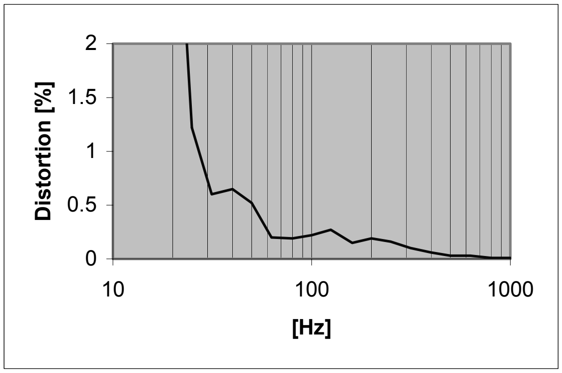

Figure 8.3-3: Rub & Buzz distortion (Based on Harmonic 10-15)

8.4. Analysis of “Rub & Buzz” Speaker

This analysis corresponds to the data used in Fig 4-4

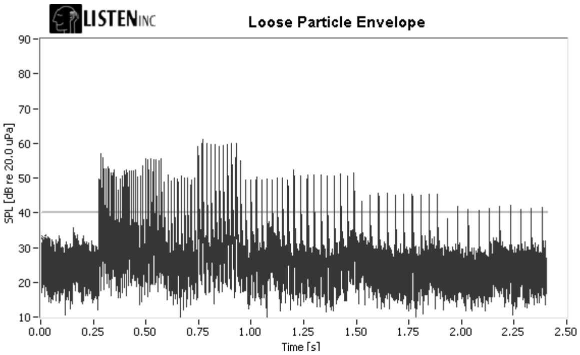

Figure 8.4-1: Time Envelope

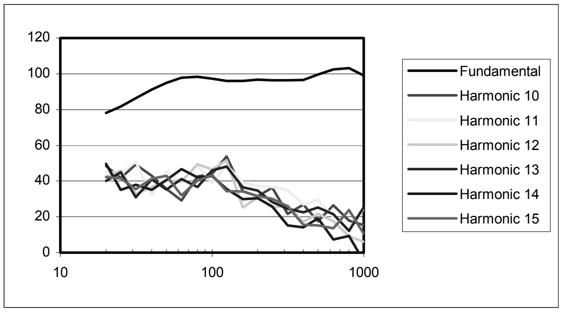

Figure 8.4-2: Harmonic Levels

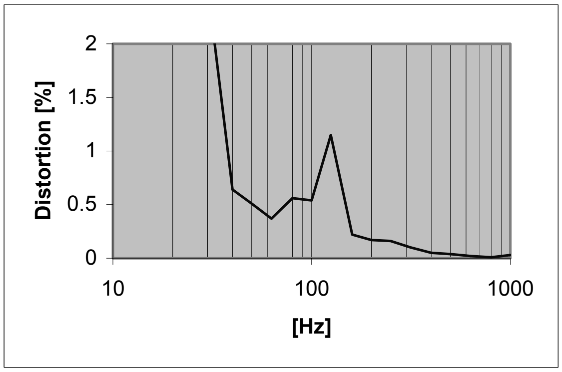

Figure 8.4-3: Rub & Buzz distortion (Based on Harmonic 10-15)

8.5. Woofer Impedance Curve

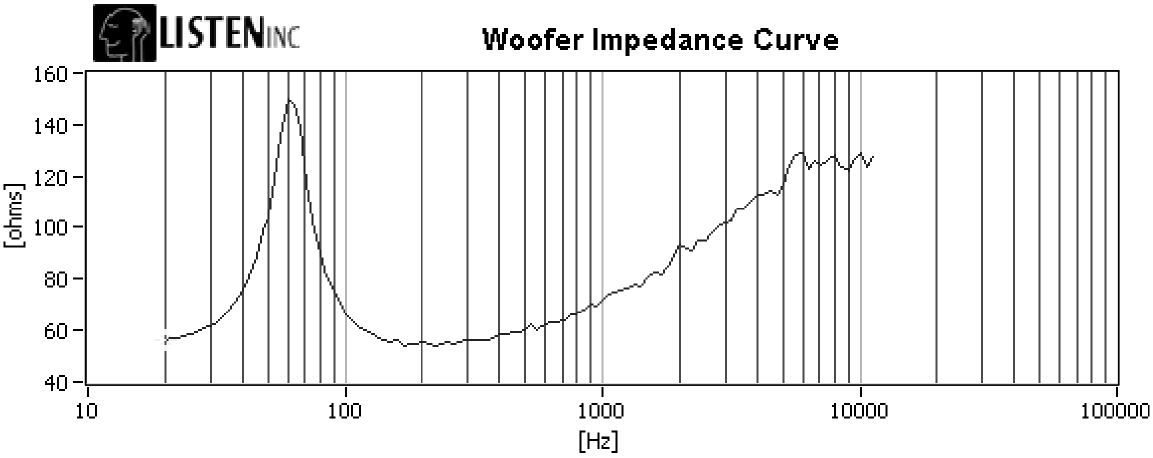

Figure 8.5