Loudspeaker Performance Evaluation Algorithm using Frequency Response Characteristic

주파수 응답 특성을 이용한 스피커의 성능 평가 알고리듬

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ABSTRACT

An algorithm for evaluating the subjective performance of a loudspeaker is proposed based on the frequency response characteristic. Objective ratings using the proposed algorithm were compared with the results of the listening test. It was verified that the ratings of the proposed algorithm showed a good correspondence with the results of the listening test.

요 약

주파수 응답 특성에 근거하여 스피커의 주관적인 성능을 평가하는 알고리듬을 제시하였고, 이 알고리듬에 의한 평가를 청취 실험과 비교하여 보았다. 청취 실험과 비교한 결과, 본 알고리듬에 의한 평가가 주관적 평가에 상당히 근접한 것을 볼 수가 있었다.

I. Introduction

There can be roughly two approaches in evaluating the performance of a loudspeaker and various methods of evaluation will fall into either one of them. One is the objective approach and the other is the subjective approach. Objective approach deals with physical parameters of a loudspeaker such as frequency response, phase response, directivity and etc. In the objective approach, the physical parameters are measured in such an objective and well defined way that it maybe repeated afterwards. From the objectively measured data, one tries to predict how the loudspeaker under test will sound in an actual circumstance. Meanwhile, in the subjective approach, performance of the loudspeaker is judged by human ear. Listening test is the most commonly used method.

Both approaches have their own disadvantages. While it's quite easy to establish objective and repeatable measuring methods to obtain the physical parameters, predicting how the loudspeaker will sound from those measured parameters alone is not simple. In the case of listening test, since the judgment of human ear varies depending on the individuals, environments and test conditions, it is not quite easy to get objective results. In practice, therefore, both approaches are used in parallel to complement each other.

Many attempts to reveal the relations between the physical parameters and the subjective performance were made. As a consequence of those attempts, not all but quite a lot of relations have been established [1], [2], [3], [4].

In an effort to predict the subjective performance of a loudspeaker, an algorithm that yields objective scores based on frequency response and directivity is proposed. These scores were produced in such a way that it can be used as criteria in judging which loud-

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speaker will sound better. To verify the validity of the proposed algorithm, the ratings based on the objective scores were compared with the results from the listening test.

II. Frequency Response of Loudspeaker

Through a large amount of experiments and researches on the loudspeaker, people were quite able to establish the physical parameters that have some relations with the subjective performance. Most widely used parameters among them are frequency response, directivity, harmonic distortion, intermodulation distortion, FM distortion, phase response and group delay [5].

Among those parameters, frequency response is considered to be the most important factor in estimating the subjective performance of a loudspeaker. A lot of studies have been revealed and investigated [1], [2], [3], [4]. Frequency response can be measured either in a free field anechoic chamber or in an ordinary reverberant listening room. Both free field and listening room response have their own meaning. While the free field response gives you only the response of a loudspeaker itself, listening room response contains the characteristics of the room as well as those of a loudspeaker. Since, in the real world, loudspeaker system is used in quite a reverberant space, the listening room response may be closer to the real situation. It is not quite sure, however, that which one will give more information about the exact subjective performance.

With regard to the microphone placement in measuring the frequency response, the microphone may be placed off axis of the center of the loudspeaker as well as on axis. The off axis response inherently contains the directivity information of the loudspeaker and it can be a certain factor in evaluating the subjective performance.

It can be thought by intuition that flatness of the frequency response curve is the most important factor. A loudspeaker with a very flat frequency response will sound very good. But there seems to be no definite threshold as to how flat should the response be and as to the audibility of the deviation from the flatness. In 1962, Bücklein found that while a peak in the frequency response curve is audible and very irritating, a dip that has the same amplitude and width is barely audible [2]. Illustration of a peak and a dip is shown in Fig. 1.

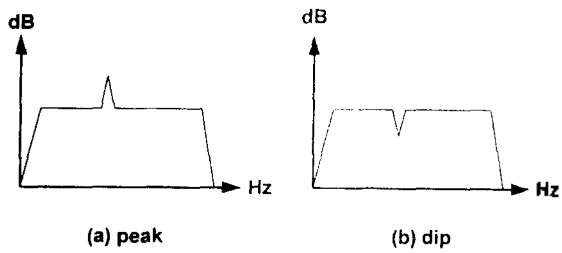


Fig. 1 an Example of a Peak and a Dip

He also found that a peak or a dip having a wider width is more audible than the shorter one [2]. This, for example, means that a loudspeaker with the frequency response of Fig. 2 (a) will sound better than the loudspeaker with the frequency response of Fig. 2 (b).

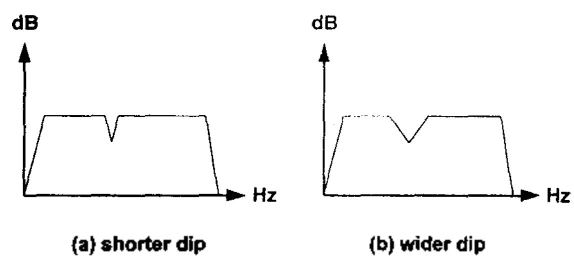


Fig. 2 Dips with Different Width

It was found through some experiments that there are two frequency regions in which the sensitivity is relatively high compared to other regions : one is between 200Hz and 600Hz and the other is between 2kHz and 6kHz [2]. It can be thought that in these regions the irregularities are more audible and the frequency response of these regions may have more influence on the subjective performance. This unequal sensitivity may have much to do with the fact that in loudness perception human ear has different sensitivity depending on the frequency component.

In Fig. 3 are shown the equal-loudness curves for pure tones. These curves imply that depending on the frequency of the signal, perceived loudness of the signals may be the same even though the physical sound pressure levels are different and vice versa. For example, an 80Hz pure tone of 70dB and a 1kHz pure tone of 60dB will be perceived with same loudness although two tones have a 10dB differebce. According to Fig. 3, the curves yield local minima

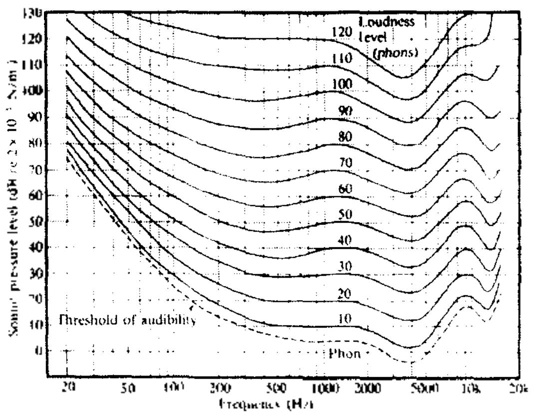


Fig. 3 Equal loudness Curves [6]

between 200Hz and 600Hz and between 2kHz and 6kHz. This means that human ear is more sensitive in those two regions compared to other regions. These minima are due to the resonance of the ear canal [6].

Ⅲ. Scoring Algorithm using the Frequency Response and the Directivity

Frequency responses of the loudspeakers under test were meansured in the listening room. Also the off axis responses were measured in order to consider the directivity of the loudspeaker. Scores predicting the subjective performance were produced using the frequency responses measured both on axis and off axis. Some psychoacoustic phenomena previously mentioned were taken into account in the scoring process.

1. Measurement of Frequency Response

Four loudspeakers, marked A, B, C, D for convenience were measured and evaluated. All of the loudspeakers under test are commercially available and are designed for hi-fi audio use. All of the frequency responses were measured in the listening room in order to come close to the real situation.

The frequency responses were measured using B&K 2012 Audio Analyzer that makes use of stepped sinewave. The frequency range of the measurement was in the range of 20Hz through 20kHz. The measuring distance was 2.5m and the listening room located in Applied Acoustics Lab at Seoul Nation University was used. The output power of the loudspeakers was set to 1 watt in the measurements. The responses of on axis, 15° off axis and 30° off axis were measured for each loudspeaker.

Each frequency response was measured more than once slightly changing the microphone placement each time and the responses were averaged. The reason for measuring the frequency multiple times is to minimize the interference caused by the wall reflections and each speaker unit.

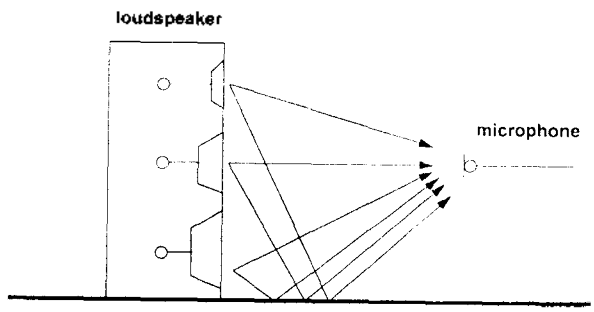


Fig. 4 Examples of Interference

Fig. 4 illustrates the interference phenomena that can occur in the listening room response measurement. These kinds of interferences give rise to peaks and dips in the frequency response curve. While these peaks and dips may be audible in monaural hearing, they are hardly audible in binaural hearing which is the common case [7].

The multiple-measured frequency responses are averaged by the following equation.

$$L_{avr} = 20 \cdot \log \frac{\sum_{i=1}^{N} 10^{L_{pi}/20}}{N} \tag{1}$$

, where L_{avr} is the averaged sound pressure level, L_{pi} is the individual sound pressure level and N is the number of responses.

The results of the measurement are as follows. Note that responses of on axis, 15° off axis and 30° off axis are plotted in one graph.

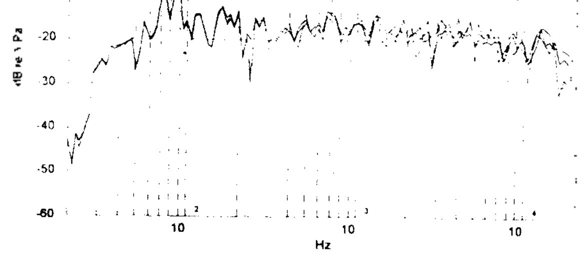


Fig. 5 Frequency Response of Loudspeaker A

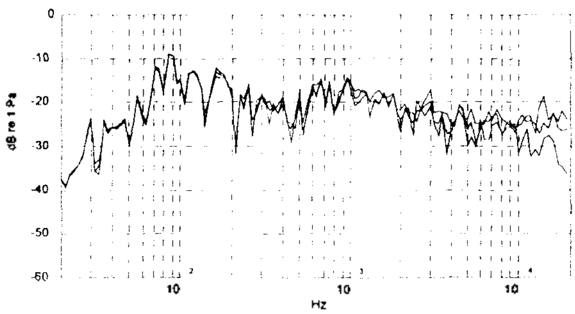


Fig. 6 Frequency Response of Loudspeaker B

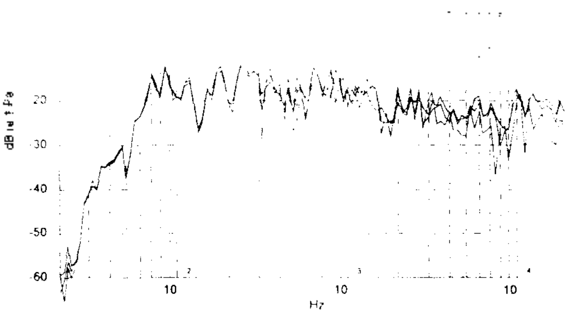


Fig. 7 Frequency Response of Loudspeaker C

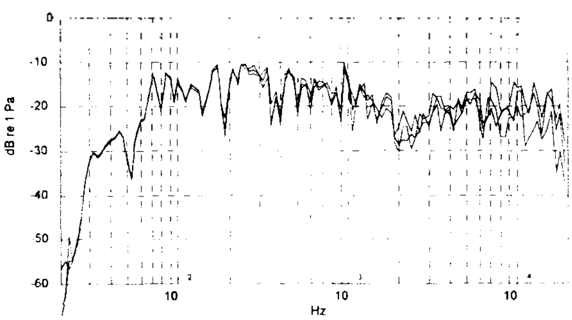


Fig. 8 Frequency Response of Loudspeaker D

2. Smoothing of the Frequency Response

The frequency response is divided into 25 bands according to human ear's critical bands. Within each band the response is averaged to give one value representing the response of the each band. By doing this, narrow peaks and dips will be smoothed. This consequence is preferable because perceptually narrow peaks and dips are not quite audible as mentioned before. With the smoothed frequency response, the overall trend of the response is easily seen. The 25 bands according to the critical bands are shown in Table 1[8].

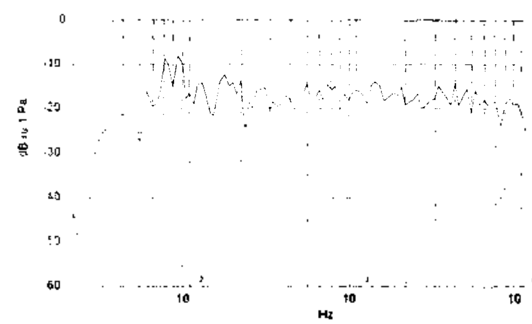
An example of smoothing is illustrated in Fig. 9.

3. Scoring Algorithm

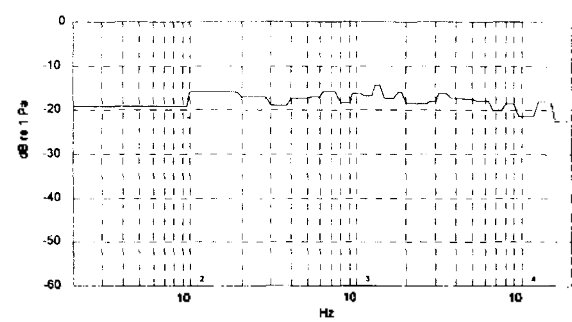
The evaluated categories are shown in Table 2.

Table 1. 25 Critical Bands

Band	Start (Hz)	End (Hz)	Band	Start (Hz)	End (Hz)
0	0	100	13	2000	2320
1	100	200	14	2320	2700
2	200	300	15	2700	3150
3	300	400	16	3150	3700
4	400	510	17	3700	4400
5	510	630	18	4400	5300
6	630	770	19	5300	6400
7	770	920	20	6400	7700
8	920	1080	21	7700	9500
9	1080	1270	22	9500	12000
10	1270	1480	23	12000	15500
11	1480	1720	24	15500	20000
12	1720	2000			



(a) Before Smoothing



(b) After Smoothing

Fig. 9 an Example of Smoothing the Frequency Response

The input and the reproduced signal of loudspeaker are, in general, music signal or speech signal. If we look at the frequency component of such signals, we can easily find that it can be divided into two regions : the fundamental frequency region and the harmonics region. For example, the spectrum of a violin playing a certain note has its frequency component

Table 2. Categories of Scores

Category	Description
Bass	The sound quality of low range sound
Mid	The sound quality of mid range sound
Treble	The sound quality of high range sound
Balance	The balance among low, mid and high range sound
Clearness	The clearness of the sound

spread over a wide range. The fundamental frequency that corresponds to the musical note is, however, quite limited. Violin has its lowest note in G3 (about 196Hz) and highest note in somewhere around C7(about 2093Hz). Thus the fundamental frequency of the violin music will be limited. Using the aforementioned concept, the fundamental region of each category is chosen appropriately based on the musical scale.

Table 3. Fundamental Regions

Category	Fundamental Region	Critical Band
Bass	C0(16.352Hz) ~ G3(196.00Hz)	band 0 ~ band 1
Mid	G3(196.00Hz) ~ E5(659.26Hz)	band 2 ~ band 5
Treble	E5(659.26Hz) ~ C7(2093.00Hz)	band 6 ~ band 12
Balance	C0(16.352Hz) ~ C7(2093.00Hz)	band 0 ~ band 12
Clearness	C0(16.352Hz) ~ C7(2093.00 Hz)	band 0 ~ band 12

In Table 3, frequencies of the notes are design-ated according to the scale of equal temperament of piano [6].

The rest of the region besides the fundamental region becomes the harmonics region. Note that since there is no absolute boundary among the low, mid and high notes, dividing the notes into three regions is somewhat subjective. The dividing process was carried out with common sense and with some help from people who major in music.

To quantify the flatness of the frequency response, the difference between the fundamental band and the harmonics band is accumulated. The accumulated index will indicate the amount of deviation from flatness. A frequency response curve that is totally flat will have the accumulated index of zero ; the increasing accumlated index will imply that deviation from flatness is large.

When accumulating the differences, more weighting is given to the more sensitive region of human ear. Assuming that sound pressure level at which we normally hear music is about 80dB re 20μPa, frequency regions between 300Hz and 600Hz and between 2.7kHz and 5.3kHz can be thought as the sensitive regions from the 80phon curve of Fig. 3. These regions correspond to band 3 through 5 and band 15 through 18, respectively. Thus the difference with the fundamental band is weighted by 2 in the band 15 through 18 and by 1.414 in the band 3 through 5.

The following is the equations that calculate the accumulated index.

$$I_{bass}=\frac{1}{2}\sum_{k=0}^{1}\Big(\sum_{n=2}|band_k-band_n|+1.414\cdot\sum_{n=3}^{5}|band_k-band_n|$$

$$+\sum_{n=6}^{14}|band_k-band_n|+2\cdot\sum_{n=15}^{18}|band_k-band_n|$$

$$+\sum_{n=19}^{24}|band_k-band_n|\Big) \tag{2}$$

$$I_{mid}=\frac{1}{4}\sum_{k=2}^{5}\Big(\sum_{n=6}^{14}|band_k-band_n|+2\cdot\sum_{n=15}^{18}|band_k-band_n|$$

$$+\sum_{n=19}^{24}|band_k-band_n|\Big) \tag{3}$$

$$I_{treble}=\frac{1}{7}\sum_{k=6}^{12}\Big(\sum_{n=13}^{14}|band_k-band_n|+2\cdot\sum_{n=15}^{18}|band_k-band_n|$$

$$+\sum_{n=19}^{24}|band_k-band_n|\Big) \tag{4}$$

$$I_{balance}=\frac{1}{13}\sum_{k=0}^{12}\Big(\sum_{n=2}|band_k-band_n|+1.414\cdot\sum_{n}|band_k-band_n|$$

$$+\sum_{n=6}^{14}|band_k-band_n|+2\cdot\sum_{n=15}^{18}|band_k-band_n|$$

$$+\sum_{n=19}^{21}|band_k-band_n|\Big) \tag{5}$$

$$I_{balance} = \frac{1}{13}\sum\left(\sum |band_i - band_k| + 2\cdot\sum |band_k - band_i| + \sum^{4} |band_k - band_n|\right) \qquad (6)$$

, where I_N is the accumulated index and $band_k$ is the value of the kth band in the frequency response. Although $I_{balance}$ and $I_{clearness}$ have the same fundamental bands, the differences among the fundamental bands are also accumulated in calculating $I_{balance}$ index due to the nature of "balance" category.

Since there are three frequency responses, there are three indexes based on three responses for each category. The listener, in general, is positioned as in Fig. 10 in the two-loudspeaker reproduction system.

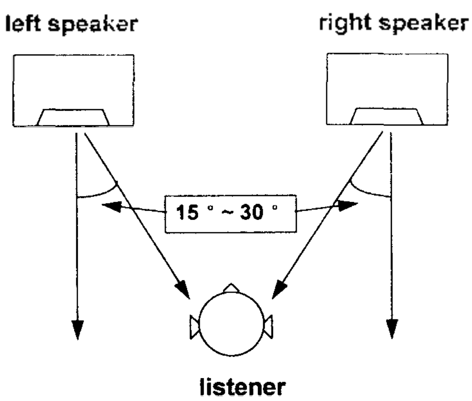


Fig. 10 Common Listener Position

It is obvious that there is much more chance for listener to be positioned off axis than on axis. In order to consider this condition, three indexes are summed with different weightings as in Equation (7).

$$I_{total} = 0.2 \times I_0 + 0.4 \times I_{15} + 0.4 \times I_{30} \qquad (7)$$

, where I_{total} is total index and I_0, I_{15} and I_{30} are indexes based on axis, 15° off axis and 30° off axis responses, respectively. Assigning the weightings were somewhat arbitrary. The weightings used in this research are only to fulfill the idea of giving more weighting to the off axis responses.

The index is converted to a score that has a maximum of 100 through Equation (8) to be able to compare with the results of the listening test.

$$S = 100 - a \times I \qquad (8)$$

, where S is the score, I the accumulated index and a the scaling factor. In this research, a was set to 0.4. The resulting scores of the loudspeakers A, B, C, D are illustrated in Fig. 11.

It can be seen from Fig. 11 that loudspeaker A has the best scores in every category by quite a margin over the others. This agrees well with the fact that the frequency response of loudspeaker A had the flattest curve among the loudspeakers under test.

IV. Comparison with Listening Test

Subjective listening test was performed in the same place where the measurement took place. Thirty nine subjects participated in the test. All were college students and in their 20s. Listening test was carried out with the same categories as with the objective scores. According to each category, different music suitable for the specified category was selected.

Comparison between two pairs of loudspeakers was made for each category. The music was played for about 20 seconds for each loudspeaker. The rating scale of the listening test for each category is shown in Fig. 12.

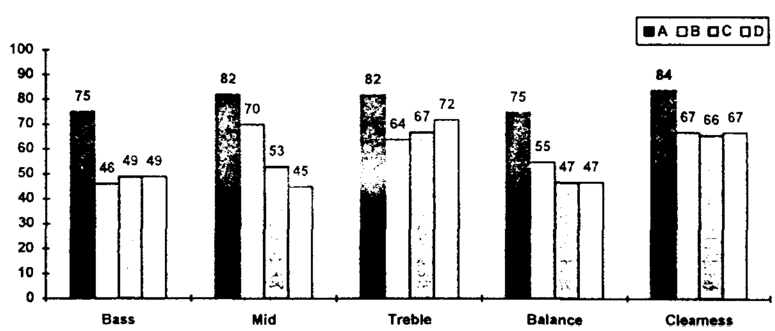


Fig. 11 Resulting Scores based on Proposed Algorithm

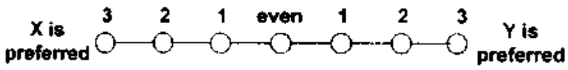
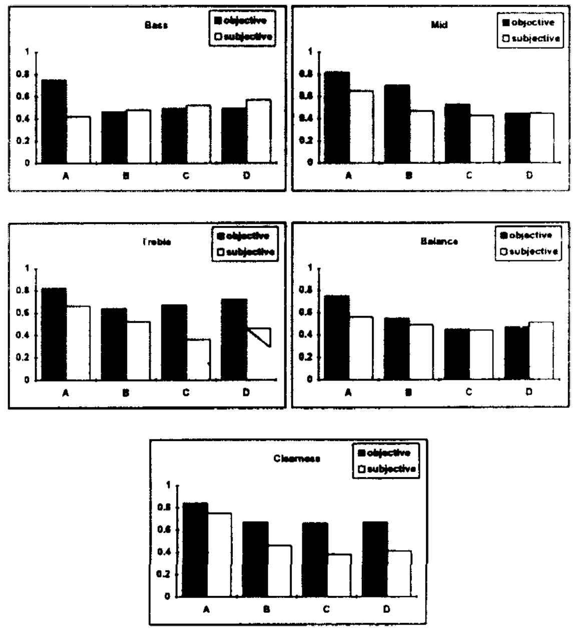


Fig. 12 Rating Scale of the Listening Test

Table 4. Music used in Listening Test

Category	Music
Bass	Excerpt from Bach's Organ Concerto in d
Mid	Excerpt from Tchaikovsky's "1812" Overture
Treble	Excerpt from Bach's Partita No.3 for Solo Violin
Balance	Excerpt from Tchaikovsky's Piano Trio
Clearness	Excerpt from Bobby McFerin's Hush Little Baby



Each loudspeaker gets a score ranging from-3 to 3 in each relative comparison. Since four loudspeakers were involved, the total score that a loudspeaker can have is between-9 and 9 for each subject. The scores of the listening test were summed up for every 39 subjects and averaged.

Table 5. Results of Listening Test

Category	A	B	C	D
Bass	-1.380	-0.312	0.384	1.308
Mid	2.772	-0.540	-1.260	-0.972
Treble	2.796	0.288	-2.436	-0.636
Balance	1.056	-0.228	-1.020	0.204
Clearness	4.560	-0.672	-2.208	-1.692

Table 5 shows the results of the listening test.

To compare the objective scores with the results of the subjective listening test, each was normalized to its maximum value.

Loudspeaker A has the best performance both in objective scores and subjective test except for the "Bass" category. In the "Bass" category, while the loudspeaker A has the best objective score, listening test shows that all four loudspeakers performed quite smilarly. This disagreement may have come from the inappropriate selection of the music used in the listening test. Pipe organ music was used in the listening test to evaluate the "Bass" category. Although it has a lot of bass components, it also yieds a lot of other frequency components. In other words, the music used in the "Bass" category had too many frequency components and this may have blurred the judgment of the subjects in the test.

Judging from the shape of the graph, the objective scores roughly follow the trend of the subjective listening test : it may well be said that proposed algorithm is able to evaluate the subjective performance of a loudspeaker system.

V. Conclusion

To predict the subjective performance of the loud speaker, a scoring algorithm based on frequency response characteristic and directivity is proposed. In this proposed algorithm, some psychoacoustic facts are considered and listening test was carried out to verify the results of the proposed algorithm.

Despite the fact that the proposed algorithm only used the frequency response and the directivity among numerous physical parameters of loudspeaker, it was able to come quite close to the actual subjective evaluation.

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