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Research Paper

Effect Analysis of Loudspeaker's Placement Angle and Direction on Frequency Response and Sound Pressure Level in TV Applications

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In a television, obtaining a good acoustic response is a challenging issue because of slim mechanical structures. The area dedicated for speaker's placement is limited and inadequate space inside the cabinet of a TV prevents possible solutions to increase the sound performance. In addition, frame of the TV's is getting narrower as the customers searching for the highest screen to body ratio. These designing aspects restrain optimal speaker positioning to achieve good sound performance. In this paper, an analysis related to speaker's placement and mounting angle is proposed. A rotation setup compatible with a TV was prepared to measure different facing position of the speaker. This paper proposes the analysis of speaker's rotation and facing direction in a flat panel television and its effects on sound pressure level together with deviation of the acoustic response. Measurement results are analyzed with an audio analyzer together with a statistics tool to achieve precise results.

Keywords: acoustic transducers; frequency measurement; frequency response; loudspeakers.

1. Introduction

In recent televisions (TVs), placement of the speakers is problematic because of the mechanical slimming trend. The main reason for this problem is a loudspeaker's requirements for sound reproduction. Speakers are electro-mechanical components and require volume to be placed in the cabinet. They need air inside/outside the cabinet to produce the sound. Large sized speakers are not suitable for slim panels due to their dimensions. Slim speakers are mostly the solution for slim panel structures but they have insufficient diaphragm surface and it has a negative impact on the sound quality such as low sound pressure level, unbalanced frequency responses, ineffective representation of low frequency areas and potential mechanical resonance problems. To optimize adverse effects of slimming trend, in other words, limited area problem in television cabinets, there have been different studies in literature. The focus of these literature studies has been on primary aspects of creating a good sound which are the most efficient speaker design and sound performance.

There are different approaches to find a solution to a limited mounting area problem for loudspeakers. After studying prior researches, these studies are categorized in two groups: new speaker structures and distortion elimination methods.

First approach of these studies is new loudspeaker structures. A different speaker structure available for flat panel TV was proposed in which a planar voice coil and a sandwich-type magnetic circuit are used for design (Bai *et al.*, 2008). A novel flat loudspeaker which uses dielectric elastomer actuators with natural rubber for the elastomeric layers and metal electrodes as transduction mechanism was introduced in another study (Rustighi *et al.*, 2018). Proposed novel loudspeaker structures are successful in acoustic results, but they may cause some problems for commercial applications due to their complicated structure. Furthermore, utilizing the technology behind ultrasonic capacitance transducers, a radically new loudspeaker concept was developed (Medley *et al.*, 2019), which resulted in the creation of an ultra-thin loudspeaker. In extension to above explained studies, a piezo based thin speaker array study was proposed as a novel structure (Been *et al.*, 2015). This study proposes a speaker structure suitable for limited dimensions but not very applicable for high quantity commercial products. Zhu *et al.* (2003) also proposes experimental results of a panel distributed speaker constructed by small actuators. Another slim speaker models for flat devices are described in (Sun *et al.*, 2012; Kwon *et al.*, 2007). There are varieties of studies which focus on space limit problem and recommend different solutions by means of mechanically slim loudspeaker unit with the combination of novel structures (Satoh *et al.*, 1997; Hwang *et al.*, 2005; Zhu *et al.*, 2003). Micro or slim speaker structures are a solution to low space problem which is the result of electronic devices mechanical design. Above mentioned novel speaker solutions are proposed to solve mechanical limit problems. On the other hand, novel structures of loudspeaker are not effective enough to solve performance problems, especially on low frequencies (Lee *et al.*, 2010; Satoh *et al.*, 1997; Hwang *et al.*, 2005; Klippel, 2005a; 2005b), and slim and rectangular shaped loudspeaker units have the problem of non-linearity and distortion (Bai *et al.*, 2008; Been *et al.*, 2015; Klippel, 2005). Distortion level of a speaker is critical for sound performance. Sound performance is quite important and should be carefully studied to improve acoustics and naturally there are different studies with the aim of optimizing distortion level. As a summary of literature work mentioned above, these studies propose novel loudspeaker structures as a solution to slimming trend but effects of placement or facing direction of these loudspeakers are not studied to extend these analyses.

On the other hand, the emergence of new speaker structures has become the basis for focusing on harmonic distortion problems and solutions. The loudspeaker converts electrical signals to pressure signals. When this situation happens, total harmonic distortion (THD) occurs. A comparison of different speaker enclosures with the analysis and results of distortion, lower total harmonic, intermodulation, and transient distortion was proposed in (Novak, 1959). To have further knowledge about distortion, sound pressure level efficiency and eliminating nonlinearities, different studies and designs for loudspeakers/enclosures were proposed in the literature as well (Nakajima *et al.*, 2015; Christensen, Olhoff, 1998; Jaskula, Mickiewicz, 2013; Hwang *et al.*, 2002; Aerts *et al.*, 2009; Ravand *et al.*, 2009; 2010; Ouaegebeur, Chaigne, 2008; Kitagawa, Kajikawa, 2009; Cruz, Martinez, 2014). Sound performance of a loudspeaker with enclosure and the theory of wave diffraction in the enclosure was also presented to understand the distortion (Dobrucki, 2006).

Another field of study is the optimization of loudspeaker characteristics such as achieving lower harmonic distortion, improvement of non-linear parameters and mechanical inconsistencies. Mechanical resonances and non-linearities affect a loudspeaker's behaviour and should be precisely optimized. Pawar *et al.* (2012) illustrated improved effect of diaphragm tracks on the sound pressure levels and THD response of elliptical miniature loudspeaker. According to the measurement results in the anechoic chamber, diaphragm tracks has no visible effect on sound pressure level, but it has effect on total harmonic distortion. Different items of a loudspeaker were studied and novel methods and studies for improving loudspeaker characteristics were presented in many research (Pawar *et al.*, 2012; Bai *et al.*, 2008; Kim *et al.*, 2009; Lee, Hwang, 2011; Merit, Lemarguand, 2008). A psycho-acoustic bass technique can also significantly improve the low frequency performance of a loudspeaker and can be used to increase frequency reproduction without distortion (Gan *et al.*, 2001). This technique doesn't increase the cost and it is effective and successful for slim structures. Due to that it produces bass voices as virtual ones it achieves good bass sound but can have an adverse effect on the frequency balance because of the artificial effects applied to the signal.

Above-mentioned studies and literature work have been proposed for neutralizing the negative effect of small sized speaker structures which is a result of slimming trend on the electronic devices. All these studies are focused on increasing efficiency of a loudspeaker to emerge a positive effect to perception of hearing. On the other hand, design limitations such as mounting conditions or placement of a speaker together with the availability for mass production, have undesired impact on these proposed solutions and decrease their efficiency. Above discussed literature studies do not contain the analysis of loudspeakers positioning and mounting scenarios in a limited space and none of them used statistical approach to precisely determine efficiency level.

In this paper, an efficiency improvement study is proposed. To understand and achieve the best efficiency point for sound reproduction, different placement angles are applied to a loudspeaker which is compatible with TV sets and an effect analysis of these positioning scenarios is analyzed with a statistics tool and results of this work are released. This paper presents the effect of the mounting angle of a speaker on the sound pressure level (SPL), critical angle values to achieve an effective frequency curve together with angle sensitive frequency range. In Sec. 2 loudspeaker placement considerations for TV sets are discussed. Details of the experimental setup and measurement results are presented in Sec. 3. Section 4 gives the conclusion.

2. Speaker placement and perceptual approach

Most of the televisions need to be slim and well-shaped because of the consumer market's need for smart looking designs and evolution of the technology. A good-looking design is a decision factor when it comes to buying an equipment in most cases. In a television, there are some parts that critically affect the TV's mechanical concept such as mainboard, power supply unit and speakers. These functions should be designed very carefully for optimum performance and speakers are the critical components which need free space on the back cover due to physical requirement of producing sound. Sound is the outcome of pressure variations and it needs a carrier for propagation like the air in front of the vibrating surface of the speaker or free air in the back cover of the TV. Dimensions of a speaker's transducer determine how much air it will oscillate. Bigger sized speakers generally produce better acoustic pressure because of higher amplitude they can create. But nowadays slimming trend in electronics limits the area for placing the speakers which means a use of limited surfaced smaller speaker structures and as a result lower SPLs. In addition to this, using smaller speakers is not a sole solution because of another visual parameter of a TV. Most of the customers seek for the highest screen to body ratio so bezels of the TV's should be as slim as possible. Figure 1 shows the comparison between a front-firing TV with a thick low side bezel which is used to place the speakers and a down-firing TV with high screen to body ratio. Borderless designs prevent placing speakers directly facing towards the customer and for this reason speakers are positioned as down fired. In down fired position there are some reflections because of the angle and these reflections may have a negative effect on the uniformity of frequency response. It causes fluctuations on the frequency response and decrease SPL for the listening position and may further affect peak/dip transition on the frequency response which are necessary criteria for tuning and sound performance.

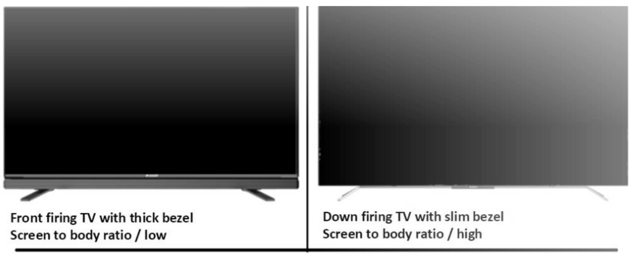

Fig. 1. Comparison of front firing structure vs down firing structure, variation of screen to body ratio with different bezel structures.

Also, there are other solutions to optimize sound quality in limited mounting dimensions such as applying mechanical enclosures to seal the air inside the speaker enclosure and prevent acoustic shortcut between front and back of the diaphragm or use of bass reflex structures to extend bass response of a loudspeaker. Using special transducers like tweeters to reproduce high frequency area or using passive radiator driver to create resonance with the loudspeaker to increase low frequency response without using bass ports are other exemplary solutions to limited space problem in TV structures. Multiple firing (back/down/front) options with more than one loudspeaker in a complete speaker set are also another way to increase sound quality. One of other method is to use mechanical parts attached to TV cabinet to guide sound waves based on reflection rules. All these solutions are effective and have significant effect on sound quality improvement, but they are all cost dependent and need additional structures or components to be implemented in TV sets productively.

Expected ideal frequency curve from a sound producing equipment is the absolute flatness but obtaining this flatness level is a very difficult issue. Because of speaker unit's non-ideal conditions, complicated response of the enclosure which the speaker unit sealed in, mechanical resonances in the units/enclosure, placement and mounting structures of the speakers cause peaks and dips on the frequency response curve. Decreasing the deviation of frequency response down to ± 3 dB range is a reasonable aim for optimizing but it is not easy to achieve also. Figure 2 shows exemplary comparison of an adjusted frequency curve with minimum deviation and non-ideal frequency curve with the large fluctuations which belongs to a TV with 25 mm width. As shown in Fig. 2 the transition of low, middle and high frequency sections is smooth in the adjusted curve and as a result the TV sounds more natural and balanced because loudspeakers are able to play all tones correctly and in a convenient proportion to each other. For most people ±3 dB is the perceivable limit. If the deviation on the frequency response increases, human ear detects fluctuation as a noise and it is perceived as unnatural. High SPL and minimum deviation on the frequency curve are the two key parameters for a good sound performance but due to recent slimming trend in consumer electronics and above- mentioned technical aspects, achieving these criteria is quite difficult.

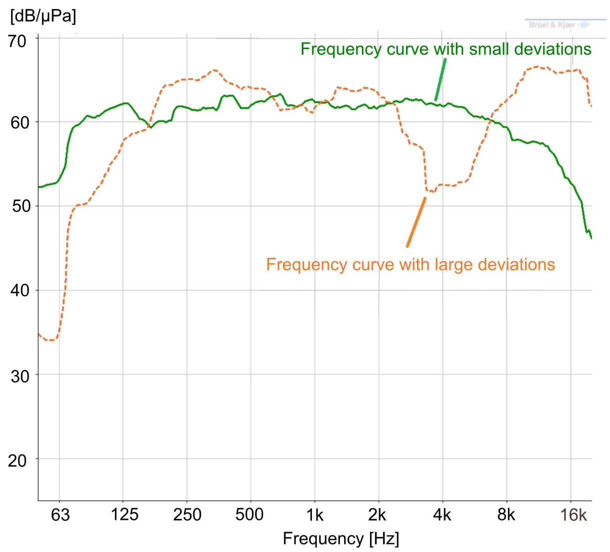

Fig. 2. Frequency curve comparison example, indication of large/small deviations.

In this paper, an analysis of a speaker structure with different installation angles is proposed. TV compatible speaker unit is placed as front-fired as an initial condition and rotated from initial condition to down-fired position. The rotation is achieved with a mechanical apparatus connected to a TV cabinet and spinning steps are executed as 5°in each turn. In every position steady state response of the speaker unit is measured from 1m distance. After the measurement stage, frequency curves are observed to find the critical placement position which proposes the best SPL and minimum curve deviation. Also angle dependent frequency ranges are determined with a comparative analysis using the frequency responses of the speaker. This paper presents the effect of the installation angle of a speaker on the SPL, critical points to achieve the best fluctuation together with the angle sensitive frequency range. The measurements were made by using high precision audio analyzer with an omnidirectional microphone. A semi-anechoic room suitable to NC25 room criteria was used for the measurement environment.

3. Experiments

3.1. Experiment setup and measurement condition

Slim structure's effect and limitations to sound reproduction was discussed in Sec. 2. To understand the effect of speaker's positioning, an experimental setup was implemented. Figure 3 shows the simplified measurement setup (sideview). As an initial condition, a flat TV with front-fired speaker was used. The back cover and mechanical mounting points were set according to front-firing structure. The TV was tested on a stand and the distance between the stand and the low side of the back cover was determined as 50 mm. 43″ TV was used for experiment and volume of the back cover was approximately 10 liters. SPL and frequency responses were measured 1m distance from the

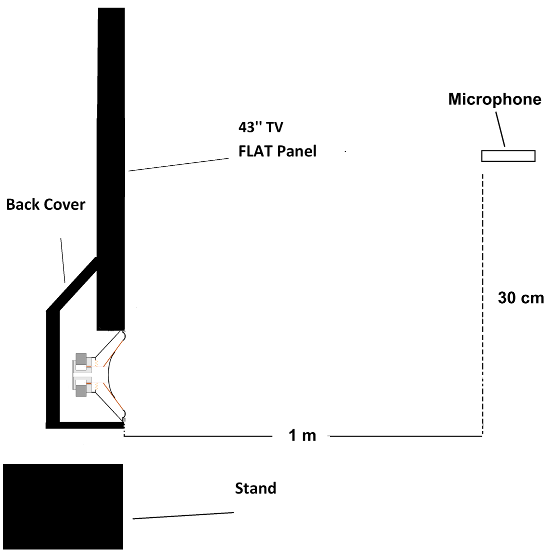

Fig. 3. Simplified measurement setup (sideview).

TV's center point. Center point of the TV's screen was selected as a reference point because nowadays there are variety of tv unit furniture with different height levels. It is difficult to estimate elevation of tv stands and customer's body position and for this reason middle point of the screen was assumed as a reference point.

After measuring initial condition, speakers are rotated with 5° increment. On every rotation, back cover and the mounting point of speakers are optimized due to mechanical changes caused by the rotation. Measurement results are obtained till reaching the final condition which is the down-firing situation. On the measurement results initial condition is expressed as 90° and the final condition is defined as 0°. Figure 4 shows the rotation steps and initial/final conditions.

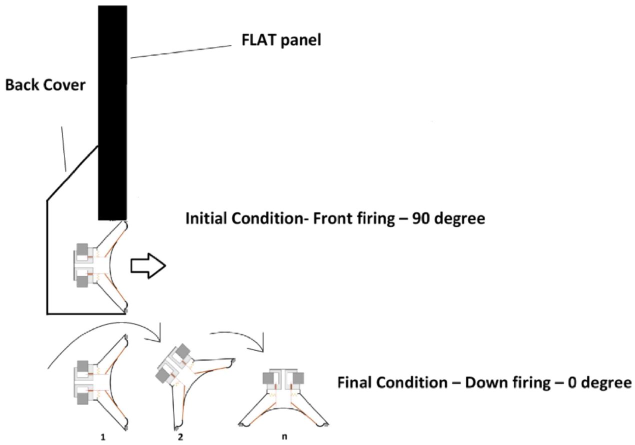

Fig. 4. Rotation steps and initial and final conditions.

The measurements results were acquired in a semi-anechoic room. To simulate the listening environment from the point of TV customers some reflective materials like stand and back wall are located inside the measurement environment. Brüel & Kjær (B&K) type 4191 high precision 1/2 inch omnidirectional microphone is used for frequency measurement. Reflections and diffractions can cause pressure increase in front of microphone diaphragm especially at higher frequencies. Free field microphone is selected for optimizing adverse effect of reflections and diffractions. Measurement results are achieved by using commercial analysis software for noise and vibration (B&K PULSE 7700) together with B&K 3560C signal analyzer. A 500 mV stepped sweep signal is applied as the input signal. The output response of the TV speakers is obtained by microphone and signal analyzer and PULSE program is used for further analysis. Individual calibration data of the microphone is inserted to the analyzer system for correction of measurement results. The summary of the measurement conditions and speaker parameters are shown in Table 1.

Table 1. Experiment equipment and conditions.

Equipment & condition	
Resonance frequency of the speaker	180 Hz
Speaker diaphragm diameter	19 × 153 mm rectangular shape
Audio Analyzer	B&K 3560c with PULSE Software
Impedance of the speaker	8 Ω
Nominal power of the speaker	10 W
Audio amplifier	Digital amp with 20 W output for each channel
Room noise criteria	NC25
Measurement distance	1 m
Frequency range of the speaker	180 Hz – 20 kHz
Microphone	B&K 4191 omnidirectional 1/2 free field mic
Microphone sensitivity	12.5 mV/Pa
Microphone frequency	3.15 Hz – 40 kHz

3.2. Experiment results

From initial condition to 0°, speakers were rotated with 5° alternation and at each angle value frequency response of the TV was measured. Figure 5 indicates comparative frequency responses of different angled setups. From the results it was measured that the rotation is effective on high-mid/high frequency range and it is measured that 1600 Hz is the critical point for proposed angle values. Because of wavelength of low-low/mid frequencies, the curves of different angles were not affected by the reflection significantly. For 1.6 kHz to 20 kHz frequency range, the results and the deviations are apparent and SPL values on this pitch were used for further analysis.

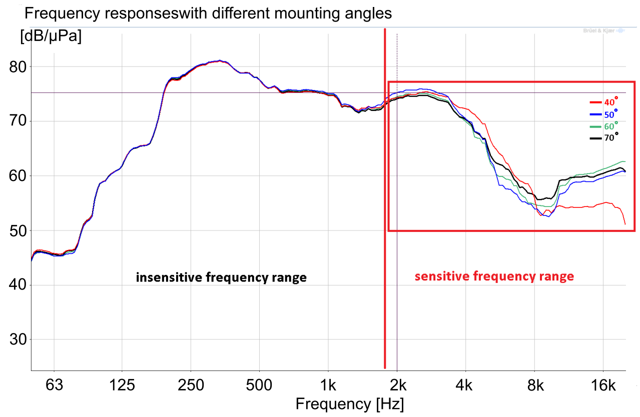

Fig. 5. Frequency responses with different angles.

Frequency sound pressure levels were converted to numbers in each frequency and for a comparative analysis a table was formed by using the values from the frequency curves. To calculate the highest SPL and lowest deviation precisely, commercial statistics tool MINITAB was used with the input values of SPL, frequency and angle of the measurement setup. By simply looking at a frequency response curve, it is not easy to figure out sound pressure level variations corresponding to different angles. From 1.6 kHz to 20 kHz, which is the main frequency area of angle effect, there are lots of frequency and SPL values. MINITAB has the function of calculating the standard deviation and mean level of angle dependent SPL data values for effective frequency range. Also, it has the feature of comparing them as a unitary data set. In the frequency-weighted evaluation of the variation in pressure levels caused by the angle change, the statistical approach and calculation method give us more precise results. ANOVA test function of the statistical tool was used for this analysis. ANOVA is a statistical test method which helps us to determine whether there is a difference between data sets, in our study which is a combination of SPL and frequency in each angle value, also shows us what is the level of difference of these compared data. Figures 6 and 7 are generated with the help of statistical tool.

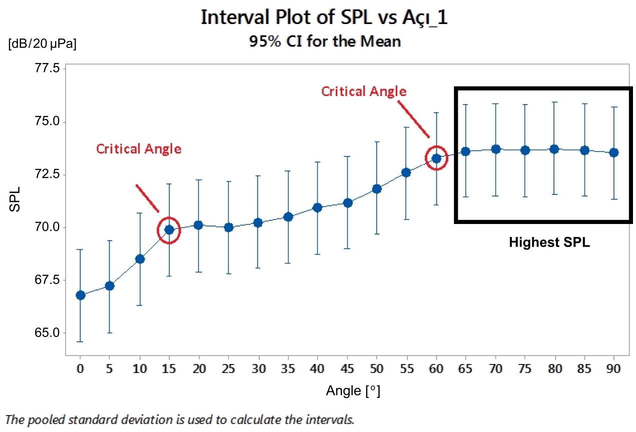

Fig. 6. Average SPL with incremental angle values.

Figure 6 indicates the average SPL with incremental angle values. From the results it is obvious that 60°

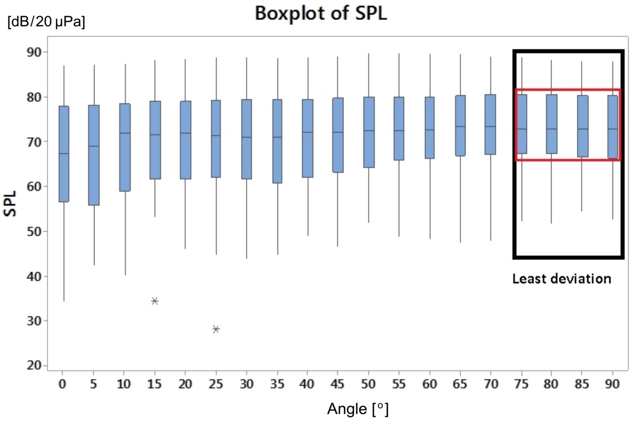

Fig. 7. Least deviation of a frequency response, measured at different angles.

point is the breakdown area. Before that area the SPL average is the highest and has a uniform distribution. But after the breakdown point the average of the SPL is decreasing almost linearly. A high SPL means that less power can be applied to the speaker and it results as low distortion.

Another critical point is the 15° rotation. Down-firing is defined as 0° and its effects can be clearly seen in Fig. 6. The lowest SPL occurs at 0°. But a 15° rotation have a good SPL average in comparison to the highest levelled angles. It can be expressed that in a down-firing positioned TV, a 15-degreed rotation to the front can be very positive for the sound performance. As discussed before ANOVA test is meant to calculate variations of a data set. If the variation in sound pressure levels corresponding to angle/frequency range combination is small, it means SPL is not varying for related angle value and it includes the feature of flatness, which is a key parameter to a balanced sound response. If the variation is big, it refers to a non-balanced frequency response and it is negative for sound reproduction as discussed in previous sections. From measurement results as boxplots which can be seen in Fig. 7, minimum variation in frequency response also signifies the mean, upper and lower values of frequency responses are in a narrow axis and it is called least deviation in our study. Least deviation is measured at 90-85-80-75 degrees. Further rotations increase the peak/dip amplitude in the frequency response and deviation starts to increase. Body of the boxplots (red marked area) in Fig. 7 shows the smallest deviation and the pin bars shows the deviation range's limits. Smallest deviation leads to balanced frequency response and it is easier for sound adjustment and helps a lot to create better hearing cases.

The main purpose of this study is to understand angle and frequency response relation. From the results it can be observed that high frequency range is sensitive to angle. All measurement results are made with a conventional loudspeaker driver. Additionally, according to measurement results conclusion of this study can be acceptable and extended to special drivers like high frequency dedicated loudspeakers in consideration of measured sensitive frequency range.

4. Conclusion

This paper proposes the analysis of speaker's rotation and facing direction in a flat panel television and its effects on sound pressure level together with deviation of the acoustic response. Flat TV dedicated experimental setup is established for this purpose. Measurement and analysis results were obtained and presented by using a high precision audio analyzer with further help of an assistant statistics tool for accurate evaluation. The effective frequency range which is dependent to angle change is determined by using the output frequency responses. Also, the impact of the angle on sound pressure level and frequency deviations are examined. The breakdown points related to the angle change are acquired. Facing direction of a TV speaker can be optimized by using these results and discussions. It should be also noted that other main criterion for sound quality is the room and its characteristics. Propagation of the sound waves is directly relevant to room structure. Room acoustics will have profound effect on the sound. Reflections, reverberations, spatialization may have different impact on human hearing perception. These room dependent features are not examined in this study to focus further of a single loudspeaker's primary characteristics. In future studies, these major components in relevant to room acoustics should be studied in suitable acoustic environment. Joint evaluation of speaker and room parameters would be a key point to achieve improved sound quality.

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