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STUDY ON THE OPTIMAL DESIGN OF A VEHICLE INTAKE SYSTEM USING THE BOOMING NOISE AND THE SOUND QUALITY EVALUATION INDEX

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ABSTRACT−In this paper, an index for the evaluation of a vehicle intake booming noise and intake sound quality were developed through a correlation analysis and a multiple factor regression analysis of objective measurement and subjective evaluation data. At first, an intake orifice noise was measured at the wide-open throttle test condition. And then, an acoustic transfer function between intake orifice noise and interior noise at the steady state condition was estimated. Simultaneously, subjective evaluation was carried out with a 10-scale score by 8 intake noise and vibration expert evaluators. Next, the correlation analysis between the psychoacoustic parameters derived from the measured data and the subjective evaluation was performed. The most critical factor was determined and the corresponding index for intake booming noise and sound quality are obtained from the multiple factor regression method. And, the optimal design of intake system was studied using the booming noise and the sound quality evaluation index for expectation performance of intake system. Conclusively, the optimal designing parameters of intake system from noise level and sound quality whose point of view were extracted by adapting comparative weighting between the booming noise and sound quality evaluation index, which optimized the process. These work could be represented guideline to system engineers, designers and test engineers about optimization procedure of system performance by considering both of noise level and sound quality.

KEY WORDS : Intake booming noise evaluation index, Intake sound quality evaluation index

1. INTRODUCTION

Because an intake noise is one of main noise-causing agent in a vehicle, not only does it cause booming noise inside the vehicle but it also plays a role that hinders comfort and sound quality inside the vehicle (Bisping, 1995). In light of this, finding countermeasure to this problem is crucial. Until recently, a design of intake system was drawn by the method of trial and error after designs of other sub-system such as engine, transmission, etc. were drawn completely (Alt, 1993). Although this may initially reduce the time involved and thus cost, in the long run, it may cause a situation where one has to pay the greater cost in finishing within a period at a later stage of vehicle development.

In addition, a noise countermeasure in low-frequency area (below 200 Hz) can cause decline of engine power as result of decrease in power or torque of engine. Until recently, a method has been used to measure mainly orifice noise in inlet end of intake system as a part of evaluating intake noise quantitatively when developing intake system of the vehicle (Otto *et al.*, 1997). However, this method has the problem since it does not consider objective measurement taken by noise and vibration expert evaluators sufficiently.

Therefore, an attempt was made to develop intake booming noise and sound quality evaluation index that are substituted for subjective evaluation to quantify intake noise in terms of noise and vibration expert evaluators on condition of wide-open throttle test of the vehicle in this thesis. Figure 1 shows flow chart of optimal design for intake system. Table 1 represents specification of test vehicles

2. OBJECTIVE MEASUREMENT OF INTAKE NOISE

2.1. Noise Source of Intake System

First, to obtain noise source of intake system, orifice noise was measured in semi-anechoic chamber where

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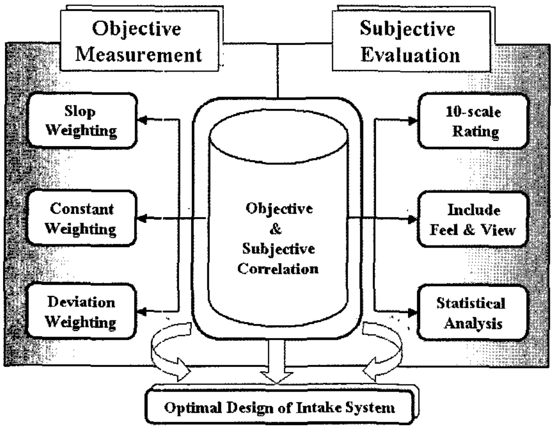

Figure 1. Flow chart of optimal design for intake system.

Table 1. Specification of test vehicles.

Vehicle	Displacement	Transmission
A	1.1 D	M/T
B	0.8 S	M/T
C	1.5 S	M/T
D	2.0 D	M/T
E	1.6 D	M/T
F	1.8 LPG	A/T
G	2.5 L6	A/T

chassis dynamo operates and measurement position was 10 mm from center of inlet end. Moreover, the measurement condition was in rapid accelerating condition that raised accelerating pedal to 2000~6000 RPM, pre-accelerating condition after fixing the third gear at manual transmission and the second gear at automatic transmission (Hashimoto, 1997; Hussain *et al.*, 1991).

A test vehicle was chosen among small and medium vehicles produced by our own company. Following Figure 2 represents objective measurement process on orifice noise of intake system in a driving condition and acoustic transfer function in a steady state. A reason to measure acoustic transfer function is to comprehend characteristic of noise caused by airborne among intake noise on interior noise of a vehicle and measure transfer function of orifice noise and interior noise to simulate the orifice noise to interior noise around driver's ear (Ko *et al.*, 2003; Lee *et al.*, 1999; Lee *et al.*, 2003). A test condition was first done by attaching a gum tape in circular form around hole on top of intake system inlet, making soft movement to hole direction by fixing a little larger iron board than hole size on top of it and attaching accelerometer outward in center of iron board. At this time, after checking connection to see if relative inflow or outflow of sound of all parts of intake system does not exist, it opened acceleration valve of a vehicle completely. Afterward, hitting the closest part to accelerometer with hammer, left and right sides of driver's seat were measured simultaneously in microphone position of interior to obtain measurement data in a form of binaural that best represents sense of hearing of human. And with measured data, an acoustic transfer function of intake orifice noise and vehicle interior noise was obtained. Following formula shows relation of intake noise and interior noise. At this point, P_{total} represents total interior noise in driver's ear position within a vehicle, P_{ci} represents contribution of intake noise among total interior noises, P_{other} represents contribution of other noise causing source except intake noise. Also P_{intake} represents orifice noise of intake system at the wide-open throttle test condition, ATF_{intake} represents acoustic transfer function of orifice noise and interior noise. As indicated in formula (1), contribution of intake noise in total interior noise can be obtained by multiplying orifice noise of intake system at the wide-open throttle test condition and acoustic transfer function between orifice noise and interior noise. At this point, particle velocity was obtained by integrating acceleration in orifice inlet end and multiplying $\rho_0 c$ with this value results in orifice noise.

$$P_{total} = P_{ci} + P_{other}$$

$$P_{ci} = P_{intake} \times ATF_{intake}$$

$$P_{intake} = \frac{P_{interior}}{P_{orifice}} \quad (1)$$

Following Figure 3 represents contribution of intake noise to interior noise of B vehicle. Figure 3(a) represents orifice noise in inlet end of intake system at the wide-open throttle test condition, Figure 3(b) shows acoustic transfer function of intake orifice noise and interior noise, and Figure 3(c) extracted intake noise components from interior noise.

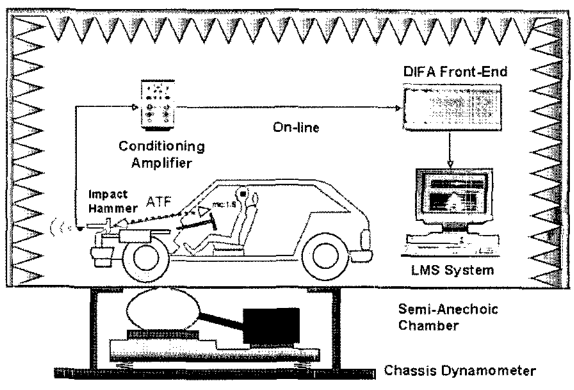

Figure 2. Test setup for the measurement of intake noise.

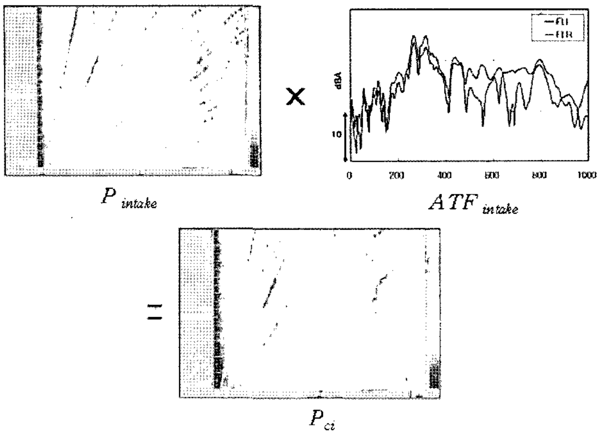

Figure 3. Contribution of intake noise to the interior noise at vehicle B: (a) Intake noise near the orifice;. (b) Acoustic transfer function between intake orifice noise and interior noise; (c) Calculated intake noise

2.2. Investigation of Psychoacoustic Parameters

Multiplying orifice noise of intake system and acoustic transfer function including sound characteristics can represent contribution degree of intake noise as to interior noise, analysis work was carried out on various measurement parameters with calculated intake noise in this way. Analysis work was performed with measured objective data as to total 100 factors including factor based on frequency, factor based on weighting and statistical factor by separating parameters based on sound pressure level and parameters based on hearing noise factors (Weisberg, 1985; Zwicker and Fastle, 1990).

In this thesis, noise level of engine firing frequency component below 200 Hz was reviewed considering most of first intake noise come from firing frequency components of engine. Moreover, loudness factors most frequently used in data analysis on existing sound pressure were reviewed. Zwicker's loudness applicable to not only free field but also diffusion field among loudness was reviewed. Also because things dealt in this thesis are about excessive signal that changes according to time, it is necessary to express objective measurement to one value quantified to compare with subjective evaluation. Based on these notions, first, after taking trend line on previously calculated intake noise under the wide-open throttle test condition, standard deviation on difference between data of calculated intake noise to obtain weighting on linearity of intake noise and trend line was obtained. After that, if slop and constant were weighted, transient signal data according to change of RPM can be represented as one value; this value becomes independent variable used in regression analysis with subjective evaluation. At this point, ratio on slop and constant of each vehicle was calculated based on average

Table 2. Psychoacoustic parameters of objective measurements.

Categories	Remarks
Index based on the sound pressure level	SPL (Linear, A, B, C, D-weighted)[2]
	Mean Value SPL (Linear, A-wei.)[2]
	Standard Deviation SPL (Linear)[2]
	Standard Deviation SPL (A-wei.)[2]
	Weighted SPL (Linear)[2]
	Weighted SPL (A-wei.)[2]
	Weighted Engine Firing Order (Linear)[2]
	Weighted Engine Firing Order (A-weighted)[2]
	1/1 Octave (Linear, A-wei.)
	1/3 Octave (Linear, A-wei.)
	Low Frequency Factor (LF, Linear)
	Low Frequency Factor (LF, A-weighted)
	Spectrum Balance (SB)[2]
	Critical Band Rate (BARK)
	Original & Weighted CRP[2]
	Original & Modify Articulation Index (AI)
Index based on the psychoacoustic parameters	Zwicker's Loudness[1,2]
	Steven's Loudness[1,2]
	Weighted Loudness (Steven's)[1,2]
	Weighted Loudness (Zwicker's)[1,2]

[1] $N_B = (N_L^{1/0.669}+N_R^{1/0.669})^{0.669}$ [2] Each frequency range
N_B: Loudness (Binaural) original, 20-200 Hz bandpass,
N_L: Loudness (Left ear) 200-510 Hz bandpass, 510-920 Hz bandpass,
N_R: Loudness (Right ear) 920 Hz highpass

value of measured vehicles in case of revising slop and constant. Table 2 shows psychoacoustic parameters of objective measurements used in analysis.

3. SUBJECTIVE EVALUATION OF INTAKE NOISE AND SOUND QUALITY

Subjective evaluation on intake noise was taken in flat driving road other than semi-anechoic chamber unlike objective measurement, which is to include feel and view, etc. that act as significant factor in subjective evaluation when driving a vehicle (Noumura and Yoshida, 2003; Schiffbanker *et al.*, 1991). Test condition set wide-open throttle test as basic, manual transmission or automatic transmission assessed intake booming noise in range of 2000~6000 RPM, and equal space criterion of 10-scale in accordance with J1060 was used as measurement criterion (Bisping *et al.*, 1997; Otto *et al.*, 1999). In addition, assessment personnel were eight noise and vibration expert evaluators, and for measurement, measurement time and driving distance were maintained equally. Moreover, statistical analysis of measurement data was

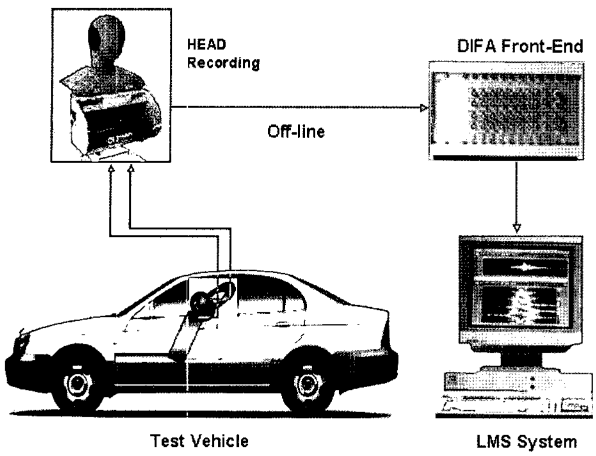

Figure 4. Test setup for subjective evaluation of intake noise.

performed using common-use software, MINITAB (Minitab, 2000; Kim *et al.*, 2003). Following Figure 4 represents test setup for subjective evaluation of intake noise when driving a vehicle.

4. DEVELOPMENT OF INATKE BOOMING NOISE AND SOUND QUALITY EVALUATION INDEX

In this thesis, slop, constant, measurement data and standard deviation of trend line were obtained using previously suggested parameters and main factors with high correlation degree were extracted through correlation analysis on subjective evaluation. A correlation analysis result suggests that noise level and loudness level of engine firing frequency component had very high correlation. Figure 5 shows characteristic curve of loudness factor with excellent subjective evaluation and high correlation degree among factors with distinctive variation among vehicles. And all correlation coefficients are about 96% according to multiple factor regression analysis among subjective evaluation and objective measurement, intake booming noise evaluation index and intake sound quality evaluation index in a linear form with correlation function as following can be obtained.

Intake Booming Noise Evaluation Index
$$= \alpha_1 - \beta_1 \times FIR^* - \gamma_1 \times ZLS^* \tag{2}$$

Intake Sound Quality Evaluation Index
$$= \alpha_2 - \beta_2 \times dBA^* - \gamma_2 \times ZLS^* \ (200\text{–}510BP) \tag{3}$$

$$\textit{Optimal Index} = 0.69 \times \textit{Sound Quality Evaluation Index} + 0.31 \times \textit{Booming Noise Evaluation}\ \text{Index} \tag{4}$$

In formula (2), *FIR** indicates sound pressure level obtained by weighting slop and constant to trend line of engine firing frequency component and *ZLS** indicates loudness level of which slop and constant were weighted to trend line. In formula (3), *dBA** indicates sound pressure level obtained by weighting slop and constant as to assumed value about trend line of A-weighted sound pressure level at the wide-open throttle test condition and *ZLS** (200–510*BP*) indicates Zwicker's loudness level of which slop and constant were weighted as to assumed value about loudness trend line in 200~510 Hz frequency region of a vehicle at the wide-open throttle test condition.

A weighting method used in present text was separated into weighting on linearity, weighting on slop and weighting on constant and numerical average value of these was set as final weighting value. In weighting on linearity, weighting value on linearity was obtained by introducing standard deviation to measure how far this trend line is from measurement data after obtaining trend line on measured data. Also, after obtaining slop on trend line of each vehicle, this was represented as ratio of dB scale to standard slop obtained by benchmarking on vehicle in weighting slop. Finally, in weighting on constant, like weighting on slop, after obtaining slop to trend line of each vehicle, this was represented as ratio of dB scale to

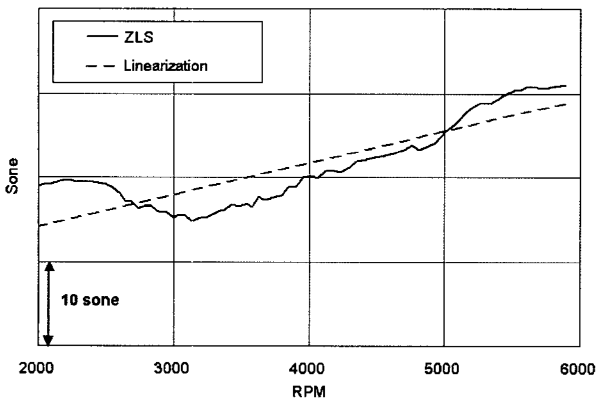

Figure 5. Level of Zwicker's loudness.

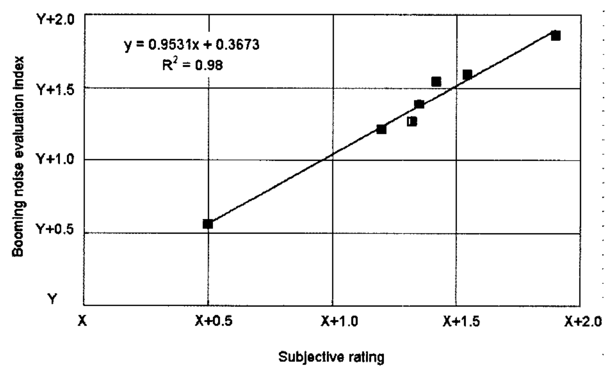

Figure 6. Regression of subjective evaluation and intake booming noise evaluation index.

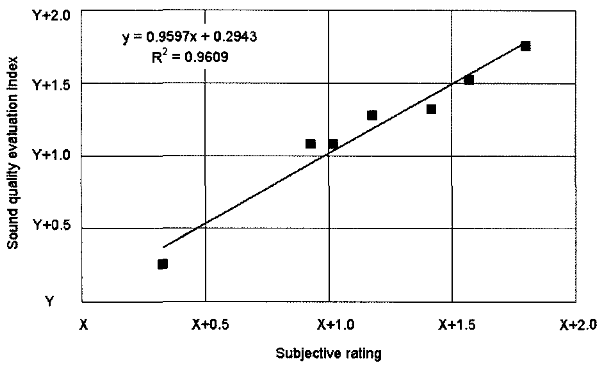

Figure 7. Regression of subjective evaluation and intake sound quality evaluation index.

standard constant. At this point, weighting value was taken as to three conditions such as slop, constant and linearity, final weighting value was obtained by averaging these three values.

Also in this thesis, a reason to weighting slop and constant is that a sound source is transient signal and it was difficult to represent as single value because of characteristics. To overcome this, a sound source was weighted to represent linearity and loudness of a sound source as single numerical value. In addition, this weighting method is applicable to general passenger car. Following Figure 6 is a result that multiple factor regression analysis was performed using subjective evaluation and withdrawn intake booming noise evaluation index, Figure 7 shows a result that multiple factor regression analysis was performed using subjective evaluation and withdrawn intake sound quality evaluation index. According to figure, under the driving condition of the wide-open throttle test, subjective evaluation and evaluation index corresponds well, correlation coefficient between two factors shows very high confidence degree more than 0.95.

5. OPTIMAL DESIGN OF INTAKE NOISE

In this thesis, we want to know which correlation the most representative two indexes such as booming noise and sound quality among intake noise have, following methods were used to give relative weighting according to that correlation degree. First, when previous noise and vibration expert evaluators evaluate intake noise, questioning as to how much weighting of booming, rumble and roar noise add indicates that most expert evaluators add about more than half weighting on booming noise and evaluate. From this, it is known that booming noise is the most representative noise of intake noise, in this thesis, draws linear trend line on FIR* component as the most dominant factor among booming noise. After that,

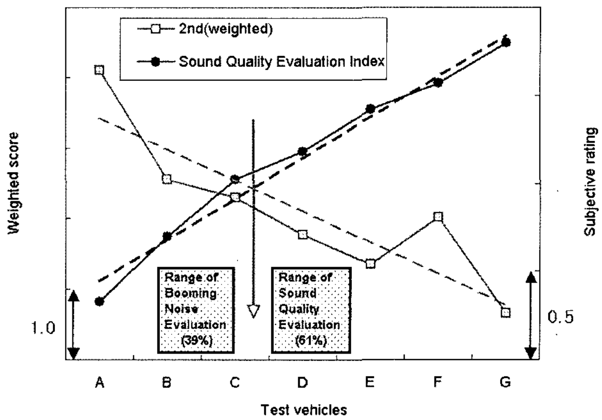

Figure 8. Comparison of intake booming noise and sound quality evaluation index.

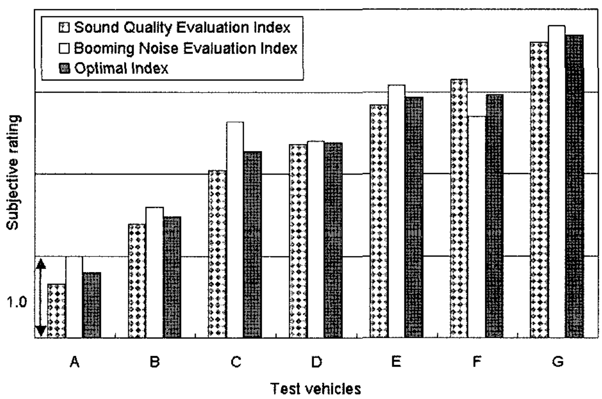

Figure 9. Comparison of each evaluation index for intake system.

drawing linear trend line on sound quality evaluation index and examining the point of crossing indicates that it meets vicinity of about 39% of the number of total vehicle (seven cars). This means that each occupying rate on booming noise and sound quality is 39 to 61 (ref. Figure 8). Therefore, in this thesis, in case of measuring total intake noise considering sound quality, relative weighting on booming noise and sound quality was measured setting as each 39% and 61% and intake system optimal index on this can be represented as following formula (4). Figure 9 is each evaluation index (booming noise evaluation index and sound quality evaluation index) for intake system was compared each other and this was compared to withdrawn optimal index. In figure, in case of E vehicle and F vehicle, booming noise evaluation index and sound quality evaluation index shows opposite result and optimal index shows almost similar result. From this, when evaluating intake system, because it is not easy to use one kind of evaluation index, to measure using optimal index combining two kinds of evaluation index is a desirable evaluation.

6. CONCLUSIONS

The following conclusions were obtained from the results above.

(1) Representative evaluation index can be withdrawn in terms of noise and sound quality by correlation analysis and regression analysis based on objective measurement and reliable subjective evaluation result on intake system.

(2) Optimization on intake system can be carried out by taking and accessing relative weighting through withdrawn intake booming noise evaluation index and intake sound quality evaluation index.

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APPENDIX

(1) Articulation Index (AI, %)

Articulation Index is a method proposed by Beranek as a more precise evaluation of speech disruption than the Speech Interference Level. The Method was later standardized as ANSI S3.5.

AI is calculated from 1/3-octave levels between 160 Hz and 6300 Hz. These weighted amplitude are then expressed as percentages according to the following diagram. The overall AI is calculated as the sum of individual AI. Standard AI is measured as a percentage, where 100% is fully intelligible and 0% is completely unintelligible.

(2) Zwicker Loudness (ISO 532-B, 1975)

Loudness assessment using the Zwicker method (standardized as ISO 532B) starts from 1/3 octave band sound pressure level data, which can originate from either a free or diffuse sound field. It is capable of dealing with complex broadband noises, which may include pure tones. The method takes masking effects into account. Masking effects are important for sounds composed of multiple components. A high level sound component may `mask' another lower level sound, which is too close in frequency. The equal loudness contours are the result of large numbers of psycho-acoustical experiments and are in principle only valid for the specific sound types involved in the test. These curves are valid for pure tones and depict the actual experienced loudness for a tone of given frequency and sound pressure level when compared to a reference tone. The resulting value is called the loudness level.

(3) Low Frequency Factor (LF)

Arithmetic mean of all unweighted octave bands below the firing frequency

$$LF = \frac{1}{N}\sum_{1}^{N} L_i$$

where, L_i: unweighted octave bands below the firing frequency

(4) Spectrum Balance (SB)
Low frequency factor minus SIL

$$SB = \frac{1}{N}\sum_{1}^{N} L_i - SIL$$

(5) Composite Rate Preference (CRP)
The Composite Rating of Preference (in dB) is an empirically established measure of sound quality based on the A-weighted SPL, the Speech Interference Level, and the Spectrum Balance.

The CRP is determined according to the following equation

$$CRP = \sqrt{L_A^2 - 1.5(L_A - SIL)^2 + 0.5SB^2}$$

where, L_A : total A-weighted SPL.

SIL : Speech Interference Level
SB : Spectrum Balance

(6) Critical Band Rate (BARK)
The inner ear can be considered to act as a set of overlapping constant percentage bandwidth filters. The noise bandwidths concerned are approximately constant with a bandwidth of around 110 Hz, for frequencies below 500 Hz, evolving to a constant percentage value (about 23%) at higher frequencies. This corresponds perfectly with the nonlinear frequency-distance characteristics of the cochlea. These bandwidths are often referred to as 'critical bandwidths' and a 'BARK' scale is associated with them as shown in below.

Critical Band (Bark)	1	2	3	4	5	6	7	8
Center Frequency (Hz)	50	150	250	350	450	570	700	840
Bandwidth (Hz)	100	100	100	100	110	120	140	150
Critical Band (Bark)	9	10	11	12	13	14	15	16
Center Frequency (Hz)	1000	1170	1370	1600	1850	2150	2500	290
Bandwidth (Hz)	160	190	210	240	280	320	380	450
Critical Band (Bark)	17	18	19	20	21	22	23	24
Center Frequency (Hz)	3400	4000	4800	5800	7000	8500	10500	13500
Bandwidth (Hz)	550	700	900	1100	1300	1800	2500	3500