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Tyre tread pattern noise optimization by a coupled source-human perception model

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ABSTRACT

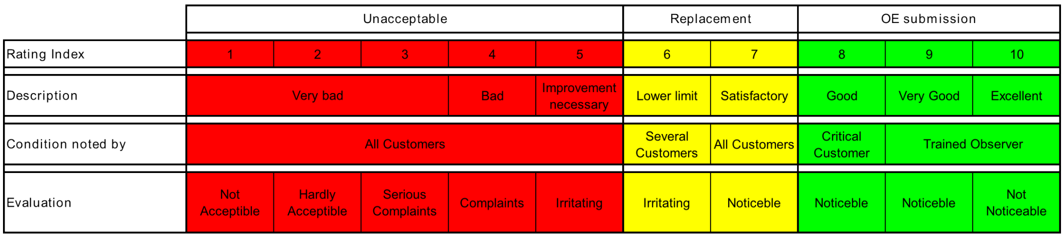
The current tyre design process uses many experimental evaluations and it may take therefore more than 2 years to develop a tyre. The use of simulation tools improves and speeds up this process. Research has shown that the human perception of tyre tread pattern noise is mainly determined by the noise characteristics: level, tonalness and modulation (also called drumming). In this paper a new source model and human perception model is described. The source modelling approach predicts the correct trends of the three tyre tread pattern noise characteristics. From the noise characteristics dedicated Sound Quality Metrics are defined: for level the Standard Deviation (STD), for tonalness the Order Prominence (OP) and for modulation the Multi- Order Modulation (MOM). Using these Sound Quality Metrics the human perception model is obtained by regression analysis, predicting the human perception of tyre tread pattern noise correctly (R^2=0.94). The coupled source - human perception model enables a very fast optimization of a complete tyre tread pattern design to human comfort.

Keywords: Tyre, Road, Sound Quality, Vehicle, Perception.
I-INCE Classification of Subjects Number(s): 11.7.1, 52.3, 63.7, 79.9

1. INTRODUCTION

1.1 Sound Quality

In the automotive industry Noise, Vibration and Harshness (NVH) characteristics of a vehicle are evaluated by an experienced test driver. This evaluation is given on a scale from 1 up to 10 according to the VDI 2563 standard shown in Figure 1. Driving manoeuvres and evaluation forms are often prescribed by the Vehicle Original Equipment Manufacturing (OEM) to obtain a common standard and terminology.



	Unacceptable					Replacement		OE submission		
Rating Index	1	2	3	4	5	6	7	8	9	10
Description	Very bad			Bad	Improvement necessary	Lower limit	Satisfactory	Good	Very Good	Excellent
Condition noted by	All Customers					Several Customers	All Customers	Critical Customer	Trained Observer	
Evaluation	Not Acceptible	Hardly Acceptible	Serious Complaints	Complaints	Irritating	Irritating	Noticeble	Noticeble	Noticeble	Not Noticeable

Figure 1 – Vehicle Original Equipment Manufacturing (OEM) rating according to VDI 2563 standard (1).

A widely used driving situation to evaluate the tyre tread pattern noise inside the vehicle is a coast down on a smooth road. During this coast down the vehicle rolls out from highway speeds of about 120 km/h to low speeds of 20 km/h with the engine shut and in free gear. The tyre tread pattern noise heard is evaluated and characterized in words using given noise terminology.

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Buss (2) analysed over more than 9500 of such coast down evaluations using a database of a tyre manufacturer. She showed that the human perception of tyre tread pattern noise is best characterized by the noise terminology: drumming noise, pattern noise and booming noise. Drumming noise is defined as an amplitude modulation of the tyre tread pattern noise. Pattern noise is described as the tonalness perception of the tyre tread patterns impact frequencies. Booming noise is the vehicles interior acoustical resonance modes.

Earlier research of Daniel (3), (4) showed that loudness is also important in the human perception of the sound. Frank (5) and Freeman (6) modelled the human perception of interior tyre-road noise using Loudness (L), spectral balance (SB) and Tonality (T) in a linear regression. Using indoor measurements of a single tyre, they could predict the subjective rating quite well.

In summary, it can therefore be concluded that drumming noise, the noise level and the tonalness are the three most important noise characteristics in the human perception of interior tyre tread pattern noise. The human perception can be modelled using Sound Quality Metrics, but is has never been coupled to a source model enabling a direct optimisation of the tyre tread pattern design to the human comfort.

1.2 Sound engineering

Regarding the sound source, the tyre industry spend many years of research reducing the tonalness by scaling the tyre tread pattern according to a so-called pitch sequence. Most of this research resulted in patents. Patents cover the developed pitch sequence, specific design rules or optimitsation methods.

Different source models have also been developed and patented. Some based upon an impulse train based representing the tread impact frequency (7), (8). More physical approaches use the tyre tread pattern geometry (9), (10), or the contact force variation (11). Hybrid approaches using measured sounds are also claimed (12). A source model predicting all three subjective noise characteristics at once or source models being coupled to the human perception models have not been reported.

Furthermore the claimed source models still require a physical tyre in order to evaluate the tyre tread pattern noise according to Figure 1. Using this approach each iteration therefore takes still about 3-4 months.

1.3 Objective

The objective of the current research is therefore to provide an engineering tool enabling a direct optimisation of the tyre tread pattern design to the human comfort. For this, two models are required:

- A source model; describing the origin of tyre tread pattern noise
- A human perception model; describing the sound quality of the tyre tread pattern noise.

The models should be coupled using Sound Quality Metrics (SQM) describing the three relevant noise characteristics: drumming, noise level and tonalness. In this manner, the coupled source-human perception model enables a direct optimisation of the tyre tread pattern design to the human noise perception.

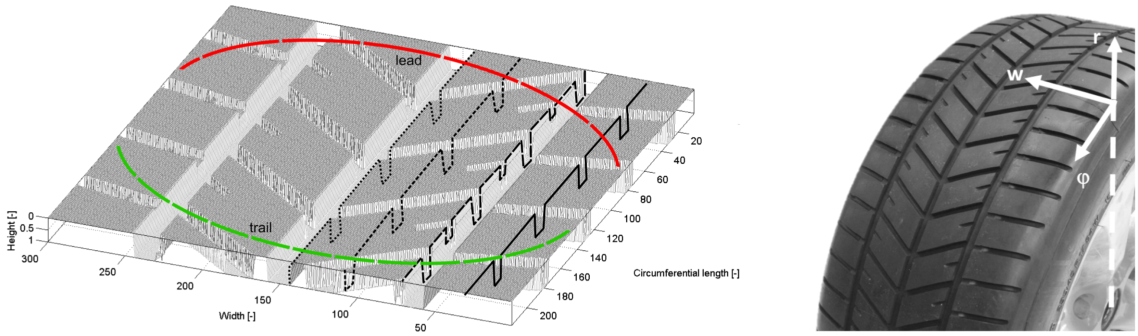

Figure 2 – Tyre with four ribs (right) and the tread pattern height (left) with the leading and trailing edges of the contact patch.

2. MODEL

2.1 Source model

Tyre-road noise originates from the contact patch between the tyre and road. Consider the tyre shown in Figure 2. The right hand side shows a tyre with a cylindrical axis system: axial direction (w), radial direction (r) and circumferential direction (φ). This tyre is used to clarify the theory and model. The left hand side of shows the tread pattern height above the groove level:

$$H_{tread}(\varphi, w) = H_0 H(\varphi, w) \tag{1}$$

where $H_0[mm]$ is a scaling factor for the maximum tread depth and $H(\varphi,w)[-]$ is the (normalized) tread pattern height. This (normalized) tread pattern height describes the shape of the tread pattern around the tyre circumference $\varphi[rad]$ and axial width $w[mm]$.

Upon rolling, this tyre tread pattern geometry passes the contact patch, resulting in contact pressure variations in both time and space. For an theoretical smooth road, the tyre which is in contact with the road is mainly responsible for the contact pressure variations resulting in tyre vibrations and noise. For simplicity, it is assumed that the complete contact patch contributes to the interior noise and all contact points (φ,w) act as coherent sources. The averaged tread pattern height in contact, as the surface integral over the contact patch per circumferential position, is therefore only relevant to consider:

$$\widetilde{h}(\varphi) = \frac{1}{A}\iint_{contact} \widetilde{H}(\varphi,w)dS \qquad \text{for all } \varphi = 0\ldots 2\pi \tag{2}$$

where A is the contact area normalizing the contact averaged tread pattern height function $\widetilde{h}(\varphi)$ between 0 and 1. As such it resembles the real contact area divided by the apparant contsct areaThe function of the example tyre is shown in Figure 3.

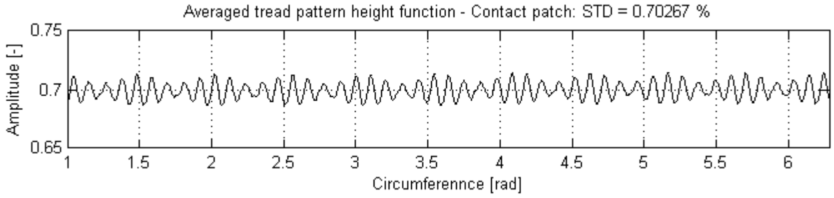

Figure 3 – Contact averaged tread pattern height versus the circumference.

As can be seen from Equation 2 and Figure 3 the contact averaged tread pattern height function $\widetilde{h}(\varphi)$ varies around the tyre circumference. The tyre tread pattern and thus $\widetilde{h}(\varphi)$ repeats itself exactly after one revolution around the tyre circumference $\varphi = 0\ldots 2\pi$. The function $\widetilde{h}(\varphi)$ is thus periodic and continuous along the circumferential φ-direction. A Fourier series reveals therefore the circumferential wavenumbers. This can be done for each axial location (w) as indicated by the lines shown in Figure 2 or for the contact averaged tread pattern height function $\widetilde{h}(\varphi)$:

$$\widetilde{h}(\varphi) = \tfrac{1}{2}a_0 + \sum_{n=1}^{\infty} A_n \cos(n\varphi + \vartheta_n) \tag{3}$$

where the A_n represents the geometrical amplitude of the circumferential wavenumber n, also called order, and is defined by:

$$|A_n| = \sqrt{a_n^2 + b_n^2} \tag{4}$$

and ϑ_n is the phase of that geometrical wave:

$$\vartheta_n = \arctan\left(\frac{b_n}{a_n}\right) \tag{5}$$

both calculated using the Fourier coefficients:

$$a_n = \frac{1}{\pi}\int_0^{2\pi} \widetilde{h}(\varphi)\cos(n\varphi)\,d\varphi \tag{6}$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} \widetilde{h}(\varphi)\sin(n\varphi)\,d\varphi \tag{7}$$

It is assumed that the interior sound pressure $p(t)$ follows the same trend as the contact averaged tread pattern height:

$$p(t(\varphi)) \propto \widetilde{h}(\varphi). \tag{8}$$

where the time $t(\varphi) = \varphi/\Omega$ with Ω is rotational speed of the tyre.

2.2 Human perception model

Using the contact average tread pattern height as the source model the trends of the three relevant tyre tread pattern noise characteristics can be predicted.

2.2.1 Level: Standard Deviation (STD)

The variation of $\widetilde{h}(\varphi)$ around its mean value results in a similar acoustic pressure variation inside the vehicle. No material stiffness, tyre transmissiblity or vehicle transfer path is taken into account. Therefore the model can be used in a comparitive manner. A simple metric describing the level of variation is the standard deviation. The standard deviation of the averaged tread pattern height function, $\widetilde{h}_{STD}$ is therefore considered to be a measure for the Sound Pressure Level inside the vehicle:

$$\widetilde{h}_{STD} = \sqrt{\int_0^{2\pi} \left(\widetilde{h}(\varphi) - \widetilde{h}_{mean}\right)^2} \tag{9}$$

The term between brackets will later be used and is the absolute deviation of each point in $\widetilde{h}(\varphi)$ from the mean, also known as the variance. In Figure 3 the calculated standard deviation is shown to be 0.70%. In order to reduce the noise level, the standard deviation of the averaged tread pattern height should be reduced.

2.2.2 Tonalness: Order Prominence (OP)

The result of the Fourier series analysis of $\widetilde{h}_{STD}$ of the example tyre is shown in Figure 4. In this so-called order spectrum the two fundamental orders corresponding with the amount of tread blocks can be identified, the58^{th} order originating from the two middle ribs and the 70^{th} order originating from the two shoulder ribs. The first harmonics of both can also be identified being 116 respectively 140. In this example tyre no pitch sequence, distributing the tread impact over more orders, is applied.

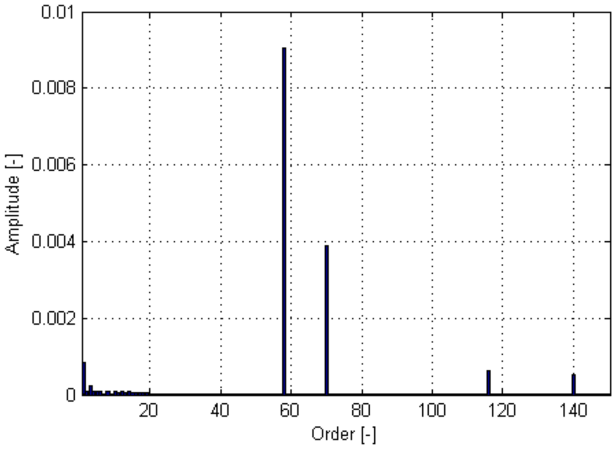

Figure 4 – Order spectrum by Fourier series decomposition of the contact averaged tyre tread pattern height of the example tyre.

Upon rotation of the tyre each circumfertial wavenumber will excite the tyre with the amplitude shown in the order spectrum resulting in an impact frequency f [Hz] according to:

$$f = n\Omega = n\frac{v}{(2\pi R)} \tag{10}$$

with n [-] is the order, Ω [Hz] the tyre rotation frequency, v [m/s] driving speed and R [m] is the rolling radius of a 235/45R17 tyre around 0.32 [m]. The order spectrum of the tyre tread pattern geometry is thus intrinsicly correlated with the tread impact frequencies (13), (14).

A dedicated Sound Quality Metric using by the Prominence Ratio (15) is derived to obtain a scalar quantity from the order spectrum describing the amount of tonalness (16). This metric sums the amplitudes of the orders in 10 order wide range (representing the critical bands). The difference of each sum with it's nearest neighbours is calculated. The maximum difference is defined as the Order Prominence (OP) value(16). As such OP is a scalar quantity, to be used as the second tyre related Sound Quality Metric in the human perception model.

2.2.3 Modulation: Multi-Order Modulation (MOM)

As mentioned, the term between brackets in Equation 9 is known as the variance $\widetilde{h}_{var}(\varphi)$:

$$\widetilde{h}_{var}(\varphi) = (\widetilde{h}(\varphi) - \widetilde{h}_{mean})^2 \tag{11}$$

and is shown for the example tyre in Figure 5.

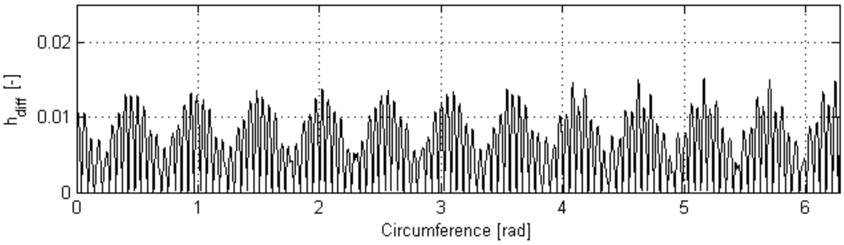

Figure 5 – Variance of the contact averaged tread pattern height $\widetilde{h}_{var}$ of the example tyre.

Twelve peaks and valleys can be identified in the signal of $\widetilde{h}_{var}(\varphi)$. These originate from a phenomenon called amplitude modulation (in acoustics called beating). Two sinusoidal signals of equal amplitude, but slight different frequencies $(\omega_1 < \omega_2)$ result in a signal of ω_1 with a modulation frequency of $|\omega_2 - \omega_1|$. For the example tyre the two fundamental orders 58 and 70 are causing a beating frequency, called here a modulation order, of 70-58=12.

Tyres with a pitch sequence have all orders and contain thus many modulations. To determine the most dominant modulations an enveloping procedure using the Hilbert Transform is applied to $\widetilde{h}(\varphi)$. A Fourier series decomposition of the envelope reveals the modulation orders. As the human perception of the modulation depends on the modulation frequency (17), a weighted sum of amplitudes of the modulation orders is applied to obtain a single scalar quantity called the Multi-Order Modulation (MOM) (16).

2.3 Sound Quality Preference Index

The outline of the Sound Quality part of the research is shown in Figure 6 and can be split in two parts once sounds are available from either a simulation or measurement. The Sound Quality calculation is the objective part calculating the Sound Quality Metrics described above. The Sound Quality Assessment is the subjective part and involves jury evaluations of the sound fragments.The human perception model is obtained by a linear regression of the subjective rating with the objective Sound Quality Metrics.

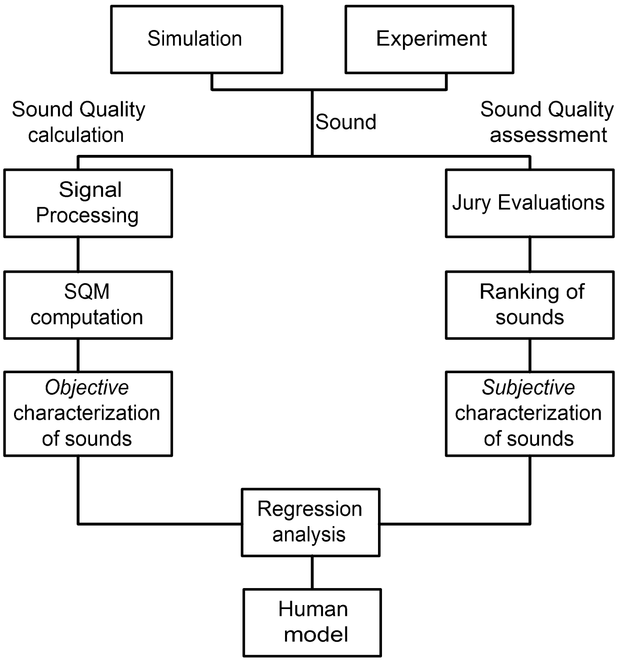

Figure 6 – Outline of Sound Quality process used for establishing and validating the human perception model.

A single subjective ranking, by which the human perception model can be fitted, is required for the human perception model. It is therefore necessary that all three Sound Quality Metrics are present in one single jury evaluation. In the current research 12 simulated sound fragments are created. The sound fragments of 3 seconds are presented by head phones to the jury using a full Paired Comparison method. The test took about 25 minutes per jury member. A small expert jury of 4 members is used, who are trained to evaluate tyre tread pattern noise on a daily basis (14).

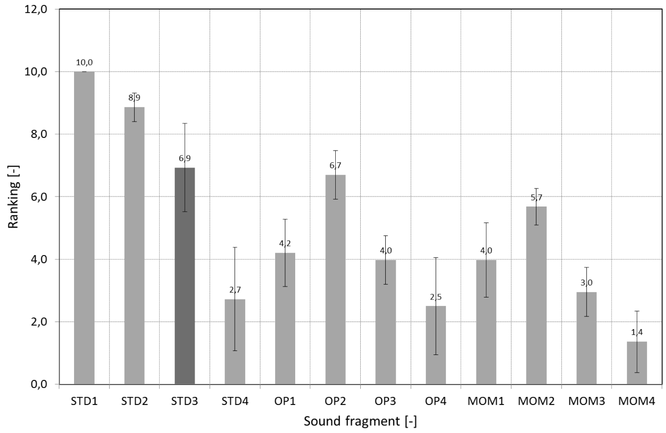

Figure 7 – Ranking of the 12 sound fragments and their standard deviation of the Sound fragments.

The results of the Sound Quality Assessment is shown in Figure 7. In this figure the average ranking of the complete jury together with the standard deviation is shown. The maximum value is normalized to 10. The STD3 is highlighted as it is the reference sound from which all other metrics are varied independently.

A linear regression of the subjective rating with the Sound Quality Metrics, STD, OP, MOM is exectuded. This results in the human perception model, called the Sound Quality Preference Index (SQPI):

$$SQPI = Y_0 - \alpha \times STD - \beta \times OP - \gamma \times MOM \tag{12}$$

where α, β, γ are coefficients and Y_0 an off-set value.

3. VALIDATION

To validate the source model the interior noise is measured of a vehicle mounted on a drum. Using 28 tyres it is shown that the STD metric predicts the trend in the Sound Pressure Level (SPL) quite well(16). Figure 8 shows the relative differences with respect to a referece tyre of the SPL (vertical axis) and $\widetilde{h}_{STD}$ (horizontal axis). Clearly a trend is seen between $\widetilde{h}_{STD}$ and the measured SPL.

The human perception model has been validated using sounds obtained by outdoor measurements. Of five different tyres the interior noise of a vehicle coasting down on a smooth road is measured. A jury assessment using headphones is executed to obtain a subjective ranking of these sounds. The SQPI of Equation 12 is used to predict the ranking. Figure 9 shows on the horizontal axis the prediction and on the vertical axis the obtained subjective ranking of the jury assessment. The high correlation indicates the quality of the human perception model.

4. CONCLUSIONS

A new methodology and modelling approach to reduce the interior tyre tread pattern noise has been proposed. The new source model describes the geometrical origin of tyre tread pattern noise with tyre tread pattern designs as an input. The human perception model describes the overall human perception of tyre tread pattern noise. Both models are validated and coupled by tyre related Sound Quality Metrics. The combined source-human perception model enables tyre designers to directly optimise the tyre tread pattern design to the human perception of the noise.

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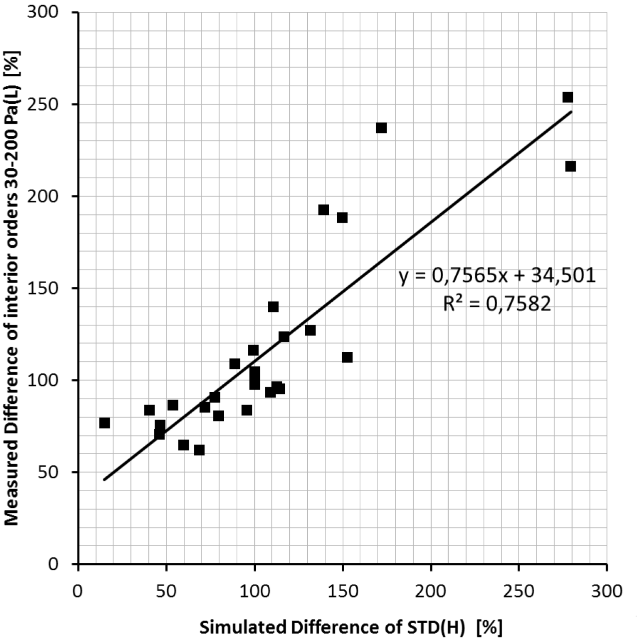

Figure 8 – Standard deviation of the averaged tread pattern height function versus the measured sound pressure level in values in percentage of a reference tyre.

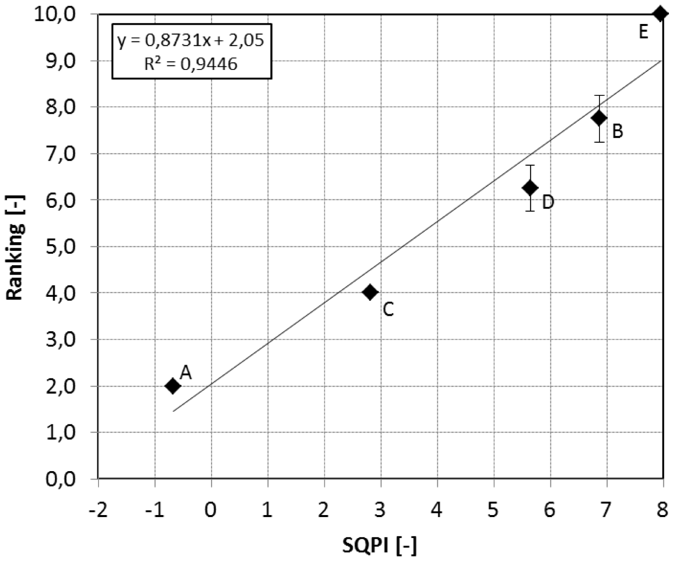

Figure 9 – Obtained ranking of jury evaluation versus the calculated Sound Quality Preference Index (SQPI).

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