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Reduction of tire noise by modifying tread pattern characteristics

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ABSTRACT

The complexity of tire/road noise generation and amplification mechanisms has made it challenging for tire builders to reduce emitted sound. Statistical methods help to model complex problems. This paper predicts tire noise level by a superior regression method in machine learning, relevance vector machine, with a total noise prediction error of 0.62 dB(A). The tire's noise sensitivity to its parameters is analyzed by applying a small central composite design to the developed model. The effect of grooves' shapes on tire noise is preserved in the results, unlike the previous publications. For a case study, grooves' depth has been recognized as critical in controlling tire noise. Based on the variance analysis results, the interaction of this parameter with the number, length, and width of transverse grooves has also been identified as significant. According to the parametric study's striking tips, two sets of tread pattern specifications are proposed for noise reduction, utilizing the response surface method. They reduce the noise level by 1.72 and 1.54 dB(A) for a tire with a measured noise of 75.88 dB(A).

1. Introduction

Since the European Community (EC) has ratified tire labeling regulations, tire/road noise reduction has been in the spotlight as a dominant noise source for passenger cars over 40 km/h. Two different approaches have been used to study tire noise, leading to design guidelines for reducing it: conducting empirical tests or investigating a mathematical model. The first way is

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more accurate than the second one. However, its limitations are that a small number of factors are examined, and the results are consequently valid for changes in parameters with limited ranges. [1, 2] reviewed most related research that used empirical tests. Associated papers have analyzed each factor's main impact on generated noise, regardless of the interactions. In this parametric study method, special tires must be produced to ensure which parameters affect the response, which requires high financial costs and special equipment.

Various mathematical models have been used to decrease tire noise, including numerical models [3-5], analytical models [6-9], or statistical models [10]. Given the complexity and diversity of different tire noise generation mechanisms, numerical and analytical models have considered only one particular source. So, they are less accurate than the statistical models that directly use empirical data. Among statistical models introduced to predict tire noise, only [10] utilized his simple polynomial regression model to reduce generated noise.

A challenge in the black-box modeling of tire noise is how to extract features from the tread pattern of tires. [10] considered physical characteristics, including the void percentage, groove angle, and the number of grooves. [11] defined more parameters for predicting tire noise using a neural network. A model to predict aerodynamic tire noise considering some tread pattern parameters was presented by [12]. A drawback of considering physical specifications is the impossibility of defining them for all tires with different patterns. Therefore, a convolutional method has been implemented that receives images directly as input. [13] examined this method using adaptive filters for only four tires, but the accuracy was not considerable. [14] achieved better accuracy using the convolutional neural network method for predicting the periodic tire noise. To cope with the high computational cost of the convolutional techniques, some papers guided the model by giving a little knowledge of the noise generation mechanisms. That helped the model learn fast and more profoundly. For instance, [15] used a pattern recognition technique. [16] regarded two spectra as neural network inputs, explaining the tire tread height change and the air volume variation rate in tire contact patch to predict tread pattern noise. [17] considered pavement specifications to determine non-tread pattern noise. These models have been provided for only specific tire geometries.

The authors' previous work comprehensively studied the statistical prediction of tire noise [18]. A robust model was developed for C1 radial tires, considering more parameters than previous publications with various geometry, operating conditions, and tread patterns. Moreover, three novel methods in this field, including support vector machine, relevance vector machine (RVM), convolutional neural network, and a new artificial neural network architecture, were compared. The selected regression model in the authors' paper, achieved using the RVM method, is examined in this research after a brief description of the modeling procedure.

This paper aims to analyze the sensitivity of the obtained model to clarify how to reduce tire noise. A potent statistical model for this aim has not been conducted in previous research unless in the author's previous paper [18]. That work examined the effects of tread pattern characteristics on noise by generating simple tread patterns that led to ignorance on the impact of grooves' shapes on results. So, this article enhances the previous procedure of parametric study focusing on each particular tire to preserve the influence of grooves' profiles on the results.

The main contributions of this research are: analyzing the tire noise sensitivity to tread pattern parameters considering grooves' shape effect, showing unprecedented interactions between factors, providing noise reduction tips, and eventually reducing tire noise using a novel method in this field, the response surface method (RSM). In this regard, a statistical model is first trained by the RVM method. Two spectra, representing air pumping and tread impact noise, are calculated to guide the model to learn faster. The resulting sound pressures are considered model inputs instead of a tread pattern image with a large size. This study employs a superior design of experiment (DOE) method, which is small central composite design (in this paper abbreviated to small-CCD), for parametric analysis. Besides, the results are utilized to design a lower noise tire by RSM. The proposed procedure for a case study would help predict and reduce tire noise with the minimum cost.

The rest of the paper is organized: Section 2 explains the experiments carried out to collect the required data. Then, the feature extraction method from the tread patterns and prediction results are presented. As a case study, Section 3 concentrates on a tire sensitivity analysis of its parameters. The outcomes are analyzed by showing interactions and employed to lower tire noise. Finally, the summary, conclusions, and future interests are given.

2. Tire noise prediction

All statistical modeling requirements, including conducting experiments, extracting features, selecting an appropriate method, and preparing data, are described here. The results are then presented and discussed.

2.1. Experiments

EU tire labeling regulations state that the noise levels labeled on tires must be measured by the coast-by method according to the international standard ISO 13325. Based on the coast-by method, the noise level of 23 C1 radial tires with specifications given in Table 1 has been recorded at the Barez tire testing track. L_R is the reported sound pressure level at the reference speed (80 km/h). Meeting the standard requirements, at least 16 spectra have been recorded by two microphones at velocities between 70-90 km/h. Noise levels of two tires (No. 10 and 21) have been measured twice to check the repeatability. Fig 1 illustrates the tread patterns of tested tires. Tire No. 2 is a smooth tire with no tread pattern. The rotating direction of all tires is downward in the figure.

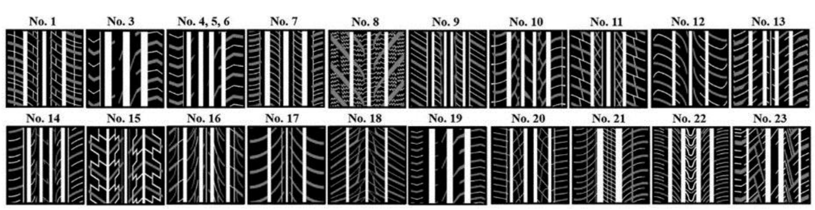

Fig 1. Tread patterns of the studied tires- Grey and white parts are tire tread grooves, and the black part shows tire tread blocks.

Table 1. Tires specifications with the noise levels measured by the coast-by method.

No.	Tire Code	Number of Spectra	L_R [dB(A)]
1	175/70R13 82H	20	73.18
2	185/65R13 80H	22	70.37
3	205/60R14 88H	23	73.84
4	205/50R16 87V	25	74.07
5	205/55R16 91V	18	72.99
6	205/60R15 91H	20	73.41
7	185/65R15 88H	24	73.02
8	165/65R13 76T	22	72.17
9	185/65R15 88H	18	73.78
10	195/65R15 91H	36	75.78
11	165/65R13 77T	28	71.75
12	165/65R13 77T	26	71.99
13	185/65R15 88H	18	74.75
14	185/60R14 82H	23	73.52
15	185/65R14 86H	22	73.69
16	205/60R15 91H	23	74.80
17	185/65R15 88H	28	75.88
18	205/60R15 90H	22	74.55
19	205/60R15 91H	21	73.88
20	205/50R16 87V	24	73.10
21	185/65R14 86H	32	72.41
22	205/60R15 91H	22	75.00
23	205/60R15 91H	22	76.15

Note: L_R: reported sound pressure level.

2.2. Feature extraction

The black-box model's input in this paper is the rim diameter, tire width, aspect ratio, load index, speed symbol, frequency, velocity, tread impact pressure, and air pumping pressure. The last two inputs are calculated by pitch noise theory [19] and Hayden theory (formulated by [7]) using the pattern image and the grooves' depth. The sound pressures due to tread impact and air pumping generation mechanisms can be written as:

$$p_{Impact}\left(r,\omega\right)=\frac{1}{r}\sum_{i}\left(\frac{A}{T}\sum_{n=1}^{N_x}\sum_{m=1}^{N_y}BW_{mn}\exp\left(j\omega t_n\right)\right)\exp\left(-j\frac{\omega}{c_c}r\right) \tag{1}$$

$$p_{AirPumping}\left(r,t\right)=\frac{\rho_a A_e}{4\pi r}\frac{\partial^2 h_g}{\partial t^2}\exp\left(j\omega\left(t-\frac{r}{c_c}\right)\right) \tag{2}$$

where p_{Impact}, $p_{AirPumping}$, r, ω, A, T, N_x, N_y, BW_{mn}, t_n, c_c, ρ_a, A_e, h_g, and t are, respectively, tread impact sound pressure, air pumping sound pressure, the distance between the microphone and tire contact patch, angular frequency, scaling factor, a cycle of rotation, number of pixels in the longitudinal direction, number of pixels in the transverse direction, corresponding matrix to the binary pattern image, the time that the tread blocks collide the road, sound speed, air density, the cross-sectional area of the pixel, groove depth, and time. Depending on the input frequency, determined pressures by the equations at the corresponding frequency are the model's inputs.

The output of the statistical model is the tire’s sound pressure level (SPL). The total number of samples is 5929, corresponding to the 539 spectra at 11 frequencies. Unlike previous papers that trained a model at arbitrary frequencies, this research uses the dominant frequency range of tire noise, 250-2500 Hz.

2.3. Method selection and data preparation

The relevance vector machine provides a sparse solution with a short training time and a small number of required training samples. The authors’ previous publication has proven this method’s higher precision in tire noise prediction than the support vector machine and the neural network [8]. RVM transfers the input vector from the input to the feature space and then employs probability functions to determine unknown weight coefficients. This method’s only hyper-parameter, related to the kernels, is optimized for the most accurate result. Details of its structure are available in the reference books [20].

This paper considers the root mean squared error (RMSE) evaluation criterion. Although the samples are adequate, they are only related to 23 tires. Therefore, the 3-fold cross-validation technique [20] can give a better assessment. All variants have been tried to be in all folds in dividing the data into three folds.

2.4. Prediction results

In addition to the model’s output (SPL), total SPL as a function of speed and reported SPL (L_R) at 80 km/h are also calculated. SPL is the black-box model’s output and depends on speed and frequency. Total SPL has been computed by summing the corresponding SPLs at different frequencies for each vehicle speed. So, the total SPL is a function of tire speed. Reported SPL is the sound pressure at 80 km/h determined by a regression analysis of total SPLs following the relevant standard. The root mean squared errors in predicting SPL, total SPL, and L_R, using 3-fold cross-validation, are reported in the first row of Table 2. It can be seen that the model is accurate enough. So, the model is re-trained using all samples as training data for afterward analysis. The RMSE of this newly trained model is given in the second row of the table. Its accuracy has increased and made the model reliable for parametric study.

Table 2. RMSE of predicted noise by RVM method.

Training Method	RMSE of SPL [dB(A)]			RMSE of Total SPL [dB(A)]	RMSE of L_R [dB(A)]
	Train	Test	Total		
3-fold cross-validation	3.23	7.59	4.28	0.83	0.56
Trian by all samples	3.19	N/A	3.19	0.62	0.38

Note: RMSE: root mean square error; SPL: sound pressure level; L_R: reported sound pressure level.

Fig 2 represents the absolute error of predicting total SPL. The maximum and minimum prediction errors are, respectively, 1.4 and 0.04 dB(A). The errors of predicting noise levels of only two tires (tire No. 2 with the lowest noise and tire No. 23 with the highest recorded noise) exceed 1 dB(A). So, the remarkable performance of RVM is evident in the figure.

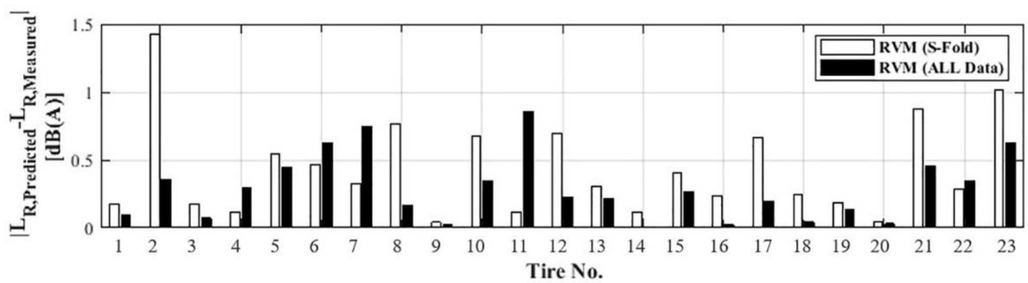

Fig 2. Noise prediction error at 80 km/h using the RVM method.

Note: L_R: reported sound pressure level; RVM: relevance vector machine.

Fig 3 demonstrates the measured and predicted frequency spectra of tires noise at the approximate speed of 80 km/h. Given the almost higher accuracy of the model in predicting spectra peaks than other frequencies, the RMSE of L_R is minor than the RMSE of SPL, as shown in Table 2. It seems that RVM has not been able to learn the spectrum of the blank tire as accurately as the other tires.

3. Sensitivity analysis and noise reduction

As mentioned in Section 1, a tire for a specific set of tire parameters has not been necessarily manufactured to examine each factor’s influence on noise. Analytical and numerical models are not also accurate enough. So, using statistical models with higher precision is beneficial for sensitivity analysis. In this regard, the statistical model implemented in the previous section, trained by all samples, is put in the place of experimentation. After designing an experiment, critical parameters are recognized. These factors are desirable because their modification significantly impacts noise compared to other factors. Even if critical parameters cannot be changed, the response depends greatly on them. The decision to modify other factors is also affected since the system response is susceptible to their values. This concept of interactions has not been raised before, and is emphasized in this paper. In this section, the parametric study procedure is performed for tire No. 17 with an almost high noise level as a case study to show how the results can be analyzed to extract tips on noise reduction. Finally, RSM is conducted to decrease noise by modifying tread pattern specifications.

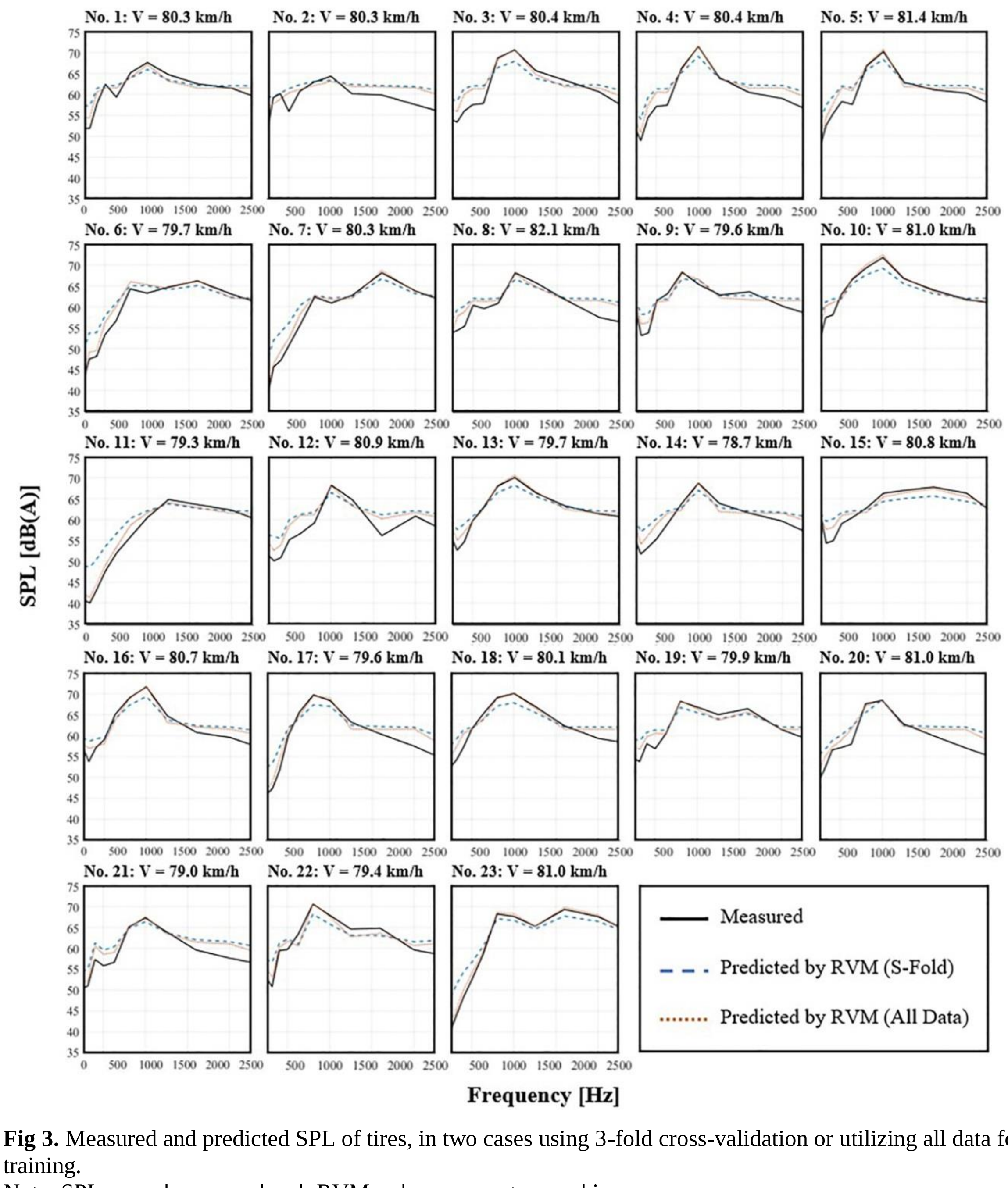

Fig 3. Measured and predicted SPL of tires, in two cases using 3-fold cross-validation or utilizing all data for training.
Note: SPL: sound pressure level; RVM: relevance vector machine.

3.1. Experiment design

The small-CCD method is a superior DOE method in designing and analyzing experiments. It is applicable in identifying sensitive factors and discovering the system's nonlinear behavior with the least number of experiments [21]. The axial points of small-CCD must be within the trained range of the model.

The effect of five factors, comprising depth, length (L_g), width (a_g), and angle of transverse grooves (θ_g), as well as their numbers in the region of the contact patch (N_g), on tire noise is investigated in this paper. Every factor (except N_g) is changed from its base to ±15%. Five numbers around the primary value of N_g are also considered the levels of this factor. The small-CCD proposes 26 factor sets to determine the L_R using RVM's model. Since the pattern image is the model's input at the pre-processing stage, the tire's initial tread pattern image is modified according to each factor's level. Fig 4 shows the patterns sketched for this aim. It must be noted that by generating tread patterns based on the initial tread pattern of the tire, grooves' shapes are preserved in the study and affects the results.

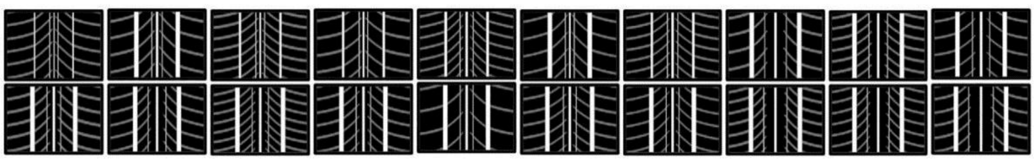

Fig 4. Generated tread patterns of tire No. 17.

3.2. Parametric study results

The implemented variance analysis (ANOVA) results in a matrix diagram, Fig 5. Each graph in this plot shows the behavior of tire noise variation when two tread pattern specifications are modified simultaneously, provided that the other three factors have not changed. Since altering tires' operating conditions and geometry is beyond designers' control, they are fixed in this sensitivity analysis. It is observed that the simultaneous change of two tread pattern characteristics can change the reported noise level up to 3 dB(A), which is considerable and worth contemplating.

The figure depicts that the groove depth is critical in controlling tire noise. A 15% decrement in this factor reduces more than 1 dB(A) of noise. Modifying the length and the width of tire grooves can also help decrease their interactions with h_g. So, examining the interaction between the parameters and slightly changing them may help reduce noise to a desirable extent. The groove angle is not an essential factor in the noise level of this tire. So, it is recommended to change h_g, L_g, a_g, and then N_g, respectively. Providing similar graphs for a tire with a known geometry reveals guidelines on how to reduce its noise. In general, decreasing all pattern-related parameters helps to lower noise. This procedure and plots are suggested to be combined with other tire design criteria, like handling, safety, and wet traction, to select the best values of pattern specifications.

3.3. Tread pattern modification to reduce noise

This section aims to reduce tire noise by modifying pattern features and using ANOVA results. It is accepted that changing pattern parameters regardless of other criteria is not logical. Nevertheless, as in previous publications, this procedure shows the model's capacity to decrease noise. For this aim, RSM in Design-Expert software is employed to lower tire No. 17's noise as a case study. This tire's measured noise level is 75.88 dB(A), and RVM's model predicts a 76.08 dB(A) sound level.

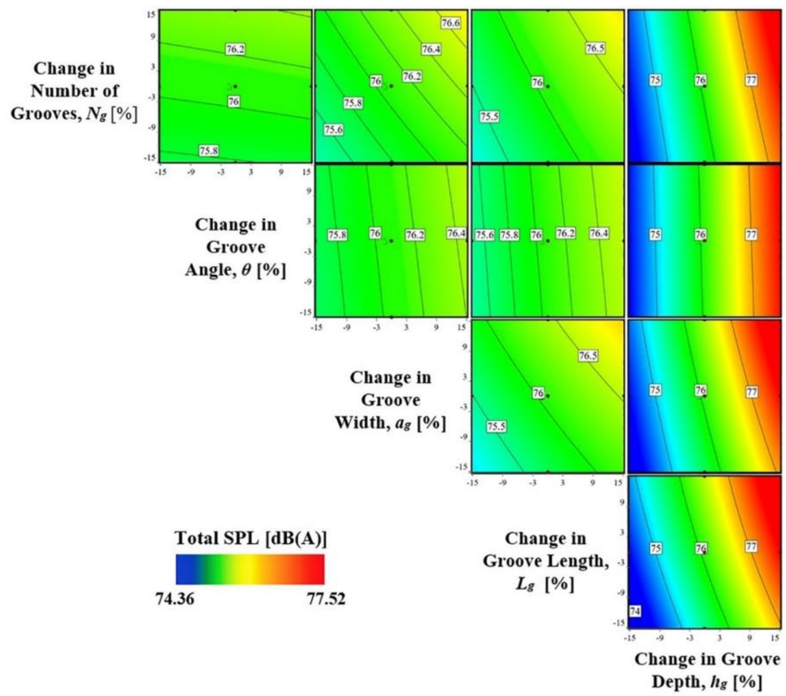

Fig 5. Total sound pressure level (total SPL) sensitivity to tread pattern parameters- tire No. 17 at 80 km/h

As resulted in Section 3.2, only by modifying the depth of transverse grooves a significant reduction can be achieved in the tire noise. Moreover, simultaneous decrement of h_g, L_g, a_g, and N_g is another option. Therefore, this section provides two suggestions for reducing the noise of tire No. 17. The first proposed modification is a 15% reduction in h_g, and the second proposal is an 8% reduction in h_g, L_g, and a_g, as well as removing one of each type of grooves in the contact patch (decreasing N_g). The parameters in the second suggestion are set on their low factorial points considered for DOE. These modifications reduce the tire's sound level to 74.36 dB(A) and 74.54 dB(A), respectively.

Fig **6**(a) presents the modified tread patterns. The 2D pattern image has not changed in the first solution, as the change has only been applied to the grooves' depth.

Fig **6**(b) shows the measured, predicted, and modified frequency spectra of the tire at 79.6 km/h. Changing the tread pattern leads to approximately equal values for most frequencies. Although the sound pressure level at the first solution's low and high frequency is higher than the second one, its lower value at the peak leads to lower total reported noise.

4. Summary/Conclusion

In this paper, the noise level of C1 radial tires has been predicted by a robust regression method, RVM. The RMSE of total noise prediction is 0.38 dB(A) at 80 km/h. Input parameters of this model are easy to access, including the geometry of the tire, its tread pattern image, and operating conditions. The trained model's pre-processing stage extracts two quantitative specifications from the tread pattern image, representing the sound pressures produced by tread impact and air pumping noise generation mechanisms. The generated model has been employed to reduce noise. The small-CCD method has been used for intelligently designing an experiment for the desired investigations. Sensitivity analysis and noise reduction methods have been performed by preserving grooves' shape effects for a case study. ANOVA has identified critical factors and their interactions. Finally, two suggestions for modification of the tread pattern utilizing RSM have been presented. They have resulted in 1.72 and 1.54 dB(A) reductions in tire noise, which is significant. The proposed procedure can unveil noise reduction ways that tire designers face nowadays.

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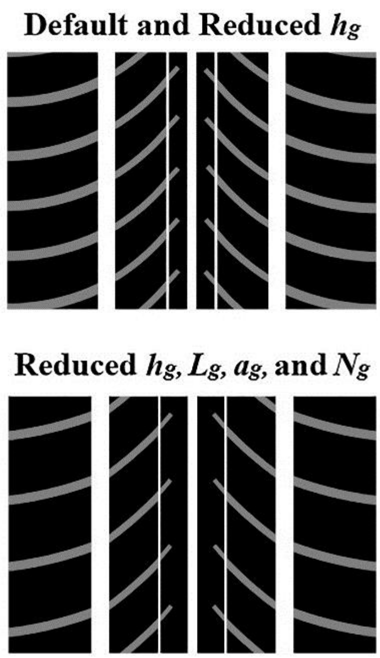
(a) 

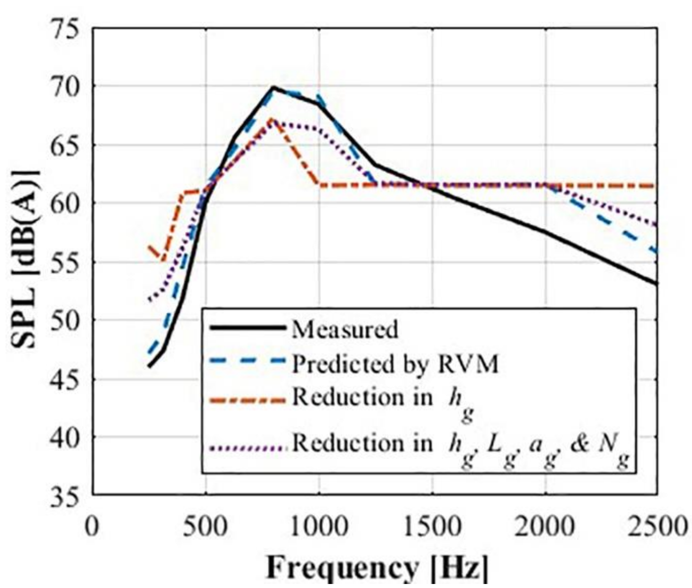
(b) 

Fig 6. Noise reduction of tire No. 17- (a) Modified patterns (b) Default and modified spectra.
Note: SPL: sound pressure level; RVM: relevance vector machine.

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