An Algorithm to Automatically Detect and Distinguish Squeaks and Rattles

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Squeak and rattle (S&R) noises are undesirable noises caused by friction-induced vibration or impact between surfaces. While several computer programs have been developed to automatically detect and rate S&R events over the years, no reported work has been found that can detect squeak and rattle noises and distinguish them. Because the causes of squeak and rattle noises are different, knowing if it is a squeak noise or rattle noise will be very helpful for automotive engineers to choose an appropriate measure to solve the problem. We have developed a new algorithm to differentiate squeak noises and rattle noises and added it to the S&R detection algorithm we had developed previously. The new algorithm utilizes a combination of sound quality metrics: sharpness, roughness, and fluctuation strength. A three-dimensional space defined by the maximum values of sharpness, roughness, and fluctuation strength of the noise are used to differentiate squeak and rattle noises.

As the overall noise level of passenger cars has been significantly reduced by recent advances in noise, vibration and harshness (NVH) engineering, the squeak and rattle (S&R) noises generated inside the passenger cabin stand out and contribute to a detrimental perception of the quality of vehicles. Market surveys conducted as early as 1983 reported the S&R as the third most important customer concern in passenger vehicles after three months of ownership.[1]

While they are often lumped together in reference, the squeak noise and the rattle noise are each generated by different mechanisms. Squeaks are friction-induced noises generated by stick-slip phenomenon between interfacing surfaces. The elastic deformation of the contact surfaces stores energy that is released and produces audible squeak noises upon the relative motion between the surfaces. Rattles are impact-induced noises generally caused by loose or overly flexible elements under-forced excitation. A number of factors, such as material property, friction coefficient, relative velocity, temperature, and humidity, are involved in S&R noises.[2]

Historically, S&R have been detected and rated by using subjective methods; therefore, the detection and rating of S&R noises often becomes an inconsistent and time-consuming process. There have been numerous efforts to develop a method to automate the detection and rating of S&Rs.[3-5] However, no work has been reported that distinguishes S&R noises after detection. Most automatic detection algorithms of S&R noises use the fact that both noises are highly transient and momentarily become discernably louder than the background noise. Therefore, it is difficult to automatically distinguish squeak and rattle noises. This article reports a special algorithm that the authors have developed to reliably distinguish squeak and rattle noises.

The authors had previously developed a computer algorithm to automatically detect and rate S&R noises.[3,6] The method developed here can be used in conjunction with the detection algorithm. At first, the detection algorithm identifies the existence of the S&R noise, then the algorithm developed in this work can be used to identify if the noise is a squeak or rattle. This will help automotive engineers to choose an appropriate approach to solve the problem.

Sound Quality Metrics

Three sound quality metrics were employed to build the algorithm, which are sharpness, roughness and fluctuation strength.

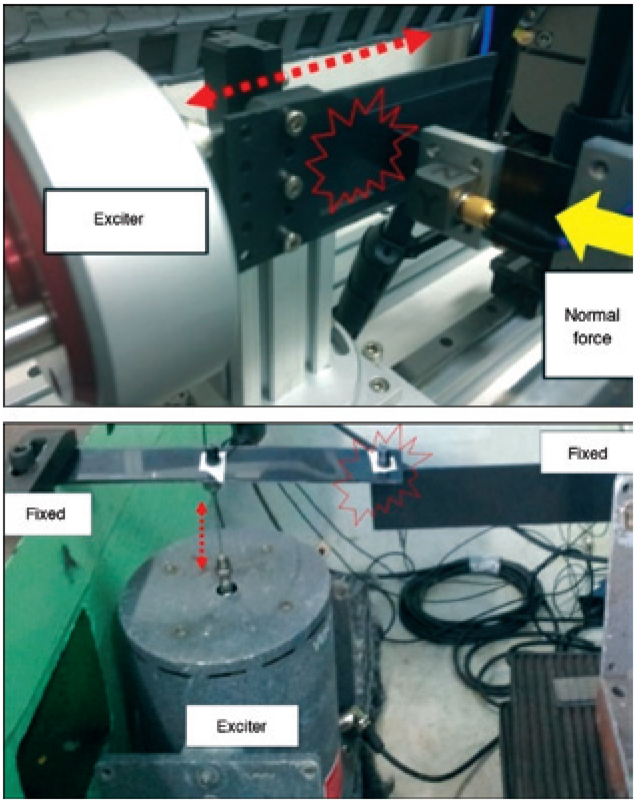

Figure 1. Experimental setup used to generate (a) squeak noises, and (b) rattle noises.

Sharpness describes the tone color of a sound in terms of its pleasantness or aggressiveness. It depends on the weighted centroid of the specific loudness (N') content. Therefore, sharpness is proportional to spectral center of gravity and is defined in Equation 1:[7]

$$S = 0.11 \frac{\int_0^{24\,Bark} N'g(z)z\,dz}{\int_0^{24\,Bark} N'dz} \tag{1}$$

where S denotes the sharpness in acum and $g(z)$ denotes the weighting function with respect to the critical band rate (z). The integral in the numerator means the first moment of specific loudness. One acum is referenced to a band of noise centered at 1 kHz at a level of 60 dB. A higher value of sharpness means higher energy in high frequency bands.

Roughness is a sensation caused by rapid temporal variation of sounds or by amplitude- or frequency-modulated tones. Roughness is represented as:[7]

$$R = 0.3 \frac{f_{\text{mod}}}{kHz} \int_0^{24\,Bark} \frac{\Delta L_E(z)dz}{dB/Bark} \tag{2}$$

where R is roughness in asper, f_{mod} is the modulation frequency, and ΔL_E is the range of excitation level within an auditory filter. One asper is defined as a 1-kHz tone at a level of 60 dB with 100% amplitude modulation at 70 Hz. Roughness increases as modulation depth of the temporal masking pattern of sounds increases. In addition, roughness is related to fast modulations.

Fluctuation strength, contrary to roughness, represents human sensitivity of relatively slow modulations. The unit of fluctuation

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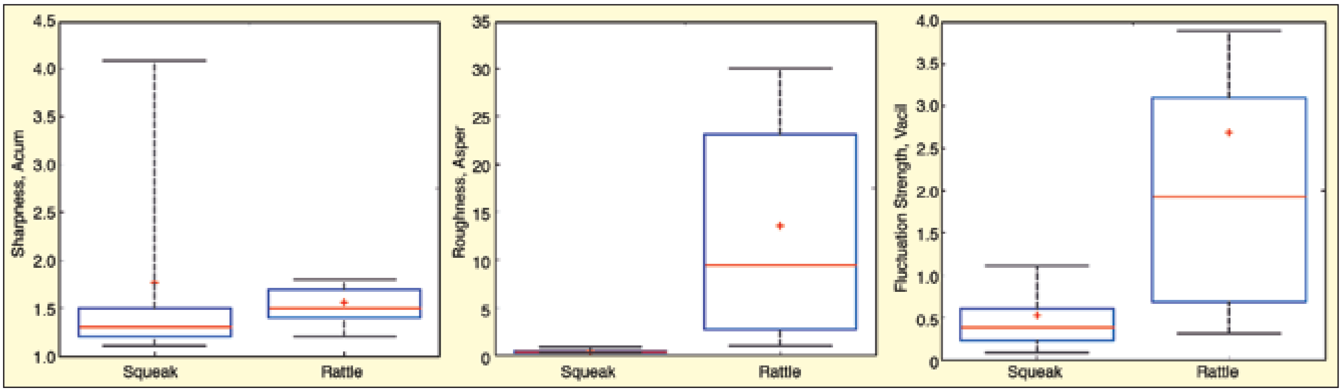

Figure 2. Box plots of maximum sound quality metrics of squeak and rattle noises produced by experiments: (a) sharpness, (b) roughness, and (c) fluctuation strength.

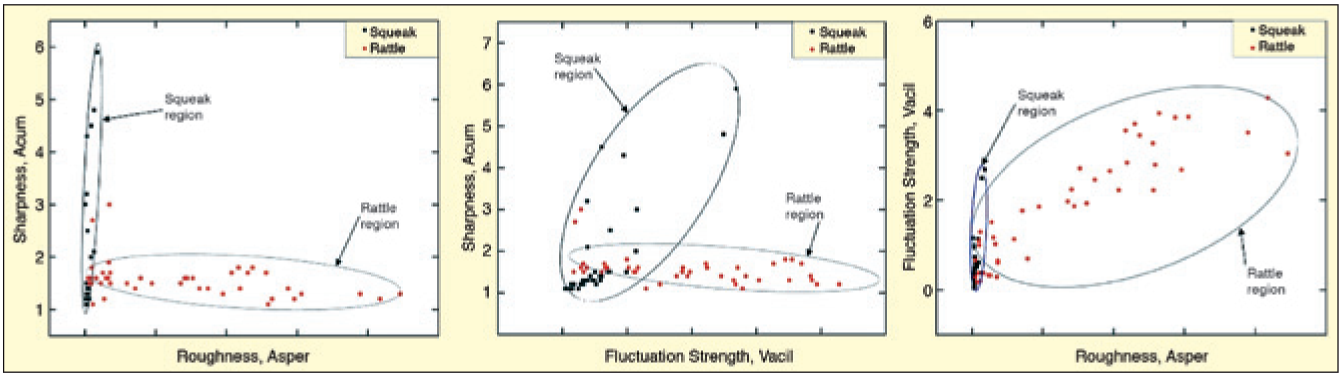

Figure 3. Squeak region and rattle region in planes of sound quality metrics: (a) sharpness-roughness plane, (b) sharpness-fluctuation strength plane, and (c) fluctuation strength-roughness plane.

strength is the vacil, and 1 vacil is referenced to a 1-kHz, 60-dB tone with 4 Hz 100% amplitude modulation. Fluctuation strength can be expressed as:[7]

$$F = \frac{0.008\int_0^{24\,\mathrm{Bark}} (\Delta L / \mathrm{dB\,Bark})\,dz}{(f_{\mathrm{mod}}/4\mathrm{Hz})+(4\mathrm{Hz}/f_{\mathrm{mod}})} \tag{3}$$

where ΔL is the masking depth, which is the difference between the maxima and the minima in the temporal masking pattern.

Experiments to Generate Squeak and Rattle Noises

Various squeak and rattle noises used in this work were generated and recorded from experiments. Figure 1 shows the experimental setups that were used to produce S&R noises. These setups were used with numerous combinations of two different materials along with 86 test noise signals. To produce squeak noise, a pair of materials was rubbed against each other.

Figure 1a is the setup used to generate squeak noises. A thin cantilever beam with one material applied on its surface was moved back and forth by a shaker while rubbing the other material on the fixed thin beam.

Figure 1b shows the setup used to generate rattle noises. A rectangular shaped piece of material mounted on the shaker was in a reciprocal motion in the vertical direction to hit the other material applied on the fixed beam. The sound pressure due to S&R noises was recorded by a microphone located 20 cm away from the contact point. The sound quality metrics of the S&R noises were calculated using the recorded sound pressure time histories.

Defining Squeak and Rattle Regions

As a preliminary analysis, the maximum value of sound quality metrics of S&R noises obtained from the experiments were calculated and compared. Figure 2 shows the distribution of the sound quality metrics of S&R noises using box plots. The means (± standard deviation) of the sharpness of the squeak noises and the rattle noises are 1.77 (± 1.15) acum and 1.56 (± 0.34) acum, respectively. The means of the roughness of the squeak noises and the rattle noises are 0.46 (± 0.34) asper and, 13.55 (± 12.51) asper, respectively. The means of fluctuation strength are 0.53 (± 0.55) vacil for the squeak noises and 2.69 (± 3.93) vacil for the rattle noises.

As shown in Figure 2, the distribution range of the sound quality metrics is very broad even though the mean values of the sound quality metrics are different between squeak and rattle noises respectively. Therefore, it is clear that squeak noises and rattle noises cannot be distinguished by using only one sound quality metric.

We attempted to construct the respective squeak and rattle regions in a space defined in terms of the three sound quality metrics. A total of 86 noise recordings were used, where each signal had been previously identified as a squeak or a rattle based on the respective test setup. Figure 3 shows the three-dimensional space of the sound quality metrics that includes the sharpness-roughness plane, sharpness-fluctuation strength plane, and fluctuation strength-roughness. Each data point represents the set of maximum values of sound quality metrics of the S&R noises generated from the experiments. For example, each point in Figure 3a represents the maximum sharpness value and the maximum roughness value of the corresponding noise. Based on the plotted sound quality metrics, the squeak region and rattle region were each grouped in an elliptical area that best characterized the data.

Distinguish between Squeaks and Rattles

Figure 4 shows the three-step procedure of the algorithm developed to distinguish squeak noises and rattle noises. As noted previously, the squeak region and rattle region in three planes of the sound quality metrics were pre-defined using the data obtained from the experiments. Without previous knowledge of the characteristics of a given noise signal, the maximum values of sound quality metrics are calculated. The type of noise subsequently is identified based on its squeak index and rattle index.

Step 1: Calculating Maximum Values of Sound Quality Metrics. In Step 1, the maximum values of the three sound quality metrics of an unknown noise are calculated. The recorded time series of the unknown noise is converted to three time series of sound quality metrics (sharpness, roughness, and fluctuation strength) by Eq. 1 through Eq. 3. Calculated over the recorded time interval, the maximum values of the metrics are used.

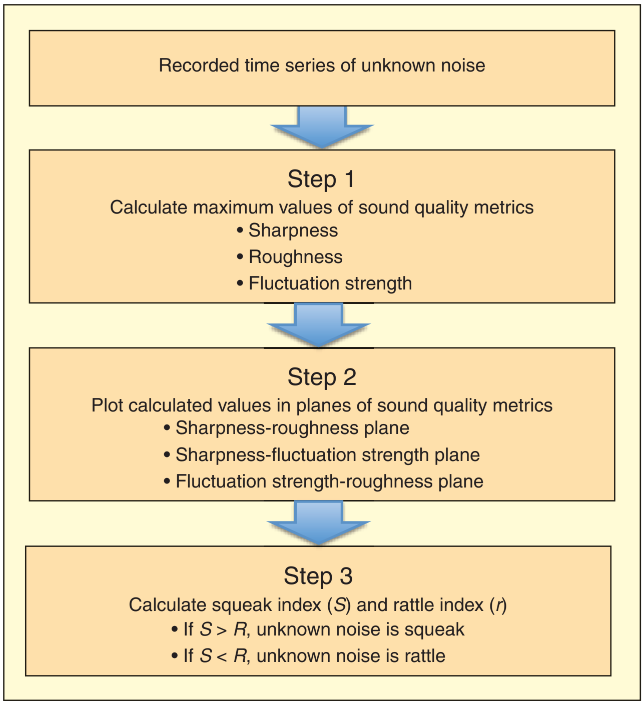

Figure 4. Procedure to distinguish squeak and rattle noises.

Step 2: Plotting Calculated Maximum Values in Planes of Sound Quality Metrics. The maximum values of the sound quality metrics calculated in Step 1 are plotted in the planes of the sound quality metrics (sharpness-roughness plane, sharpness-fluctuation strength plane, and fluctuation strength-roughness plane), which are defined in the previous section as shown in Figure 3.

Step 3: Calculation of Squeak Index and Rattle Index. Squeak index (S) and rattle index (R) are defined to distinguish squeak noises and rattle noises. Prior to calculation of S and R, squeak sub-indices (S_1, S_2, and S_3) and rattle sub-indices (R_1, R_2, and R_3) are calculated. Figure 5 illustrates how S_1 and R_1 are calculated in the sharpness-roughness plane. P represents the point corresponding to the sharpness and the roughness values of the noise whose type is unknown, C_S and C_R represent the center points of the squeak region (or ellipse) and the center of the rattle region (or ellipse), respectively. S_1 and S_1 are defined as:

$$S_1 = \frac{d_S}{l_S} \quad \text{and} \quad R_1 = \frac{d_R}{l_R} \tag{4}$$

where l_S and d_S are the distance between C_S and P, and the distance between C_S and a point of intersection between the boundary of the squeak region and l_S, and l_R and d_R are the distance between C_R and P, and the distance between C_R and a point of intersection between the boundary of the squeak region and l_R, respectively.

S_1 is higher than 1 if the unknown noise P is located inside the squeak region, and lower than 1 if P is located outside the region. Therefore, higher S_1 value means that P is located closer to the center of the squeak region. The same discussion can be made for R_1. That is, R_1 becomes higher if P is located closer to the center of the rattle region. Applying the same algorithm to all three planes (sharpness, roughness, sharpness-fluctuation strength, fluctuation strength-roughness) S_2 and R_2 are calculated in the sharpness-fluctuation strength plane, and S_3 and R_3 are calculated in the fluctuation strength-roughness plane. Once all sub-indices are calculated, the overall squeak index and the overall rattle index of the noise, S and R, can be represented as Eq. 5.

$$S = S_1 \cdot S_2 \cdot S_3 \quad \text{and} \quad R = R_1 \cdot R_2 \cdot R_3 \tag{5}$$

The algorithm identifies whether the given noise is rattle or squeak by the S and R numbers. That is, if S is bigger than R, the unknown noise is classified as squeak noise and vice versa.

Testing the Algorithm

A total of 41 squeak noises and 45 rattle noises obtained from the experiments were used to test the performance of the algorithm developed in this work. The algorithm was applied to these 86 acoustic signals whose types are known. The results are summarized in Table 1. All squeak noises were identified as the squeak noise by the algorithm, and 36 of 45 rattle noises were identified as the rattle noise. The overall accuracy of the algorithm was 89.5%.

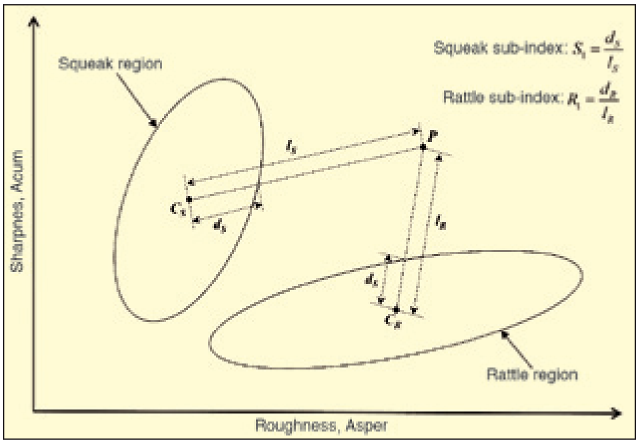

Figure 5. Calculation of squeak sub-index (S1) and rattle sub-index (R1) in sharpness-roughness plane. P represents maximum sharpness and roughness of unknown sound. CS, lS and dS are center of squeak region, distance between CS and P, and distance between CS and point of intersection between boundary of squeak region and lS, respectively. CR, lR, and dR are center of squeak region, the distance between CR and P, and distance between CR and point of intersection between boundary of rattle region and lR.

Table 1. Classified squeak and rattle events by the algorithm to distinguish squeak and rattle noises.

	No. of Specimens	No. Classified as Squeak	No. Classified as Rattle	True	False
Squeak	41	47	0	100%	0%
Rattle	45	9	36	80%	20%
Total	86	50	36	89.5%	10.5%

Discussion and Conclusion

Because the causes of the squeak noise and rattle noise are very different, knowing the type of noise can be very helpful for engineers. The developed algorithm may be used in conjunction with an S&R detection algorithm such as the one developed by the authors.[3,6]

One limitation of this work is that we developed the algorithm to distinguish squeak and rattle noises using only the noises generated on the test bench. More tests with S&R noises recorded in real car tests will further validate the performance of the algorithm.

Acknowledgments

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