Development of a test apparatus that consistently generates squeak to rate squeak propensity of a pair of materials

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ABSTRACT

Squeak is an undesirable noise generated by friction-induced, self-excited vibration of two contacting surfaces. Due to the highly non-linear nature of the underlying mechanism, it is very difficult to develop a systematic procedure to address squeak problems in automotive engineering. Obviously it is impractical to eliminate all possible sliding contacts in a vehicle, but a good structural design will minimize occurrence of contacts. For example, potential contact areas may be identified by structural analysis in the design stage, and pairs of materials that have low squeak propensity may be used for such areas. A unique squeak test apparatus was built to enable quantitative rating of squeak propensity of a given materials pair. The mechanism utilizes a sprag-slip mechanism to induce unstable vibration of a given materials pair in a consistent and repeatable manner. An analytical model was developed to understand dynamic characteristics of the test set up and refine the design of the apparatus. Unstable motions and sounds generated by the apparatus were measured for several pairs of materials, and a squeak detection and rating algorithm previously developed by the authors was applied to quantify squeak propensities. The developed procedure will be used to build material database to help NVH engineers to deal with squeak problems in the design stage.

Keywords: Squeak test apparatus, Friction-induced vibration, Sprag-slip mechanism, Analytical model, and Material pair testing

1. INTRODUCTION

Squeak is an undesirable, annoying noise generated by a self-excited vibration induced by friction force between two surfaces in sliding contact. Because of the highly nonlinear nature of the phenomenon, it is known as one of the most difficult problems for NVH engineers to deal with. Three mechanisms are known that lead to friction-induced, self-excited vibration. The stick-slip phenomenon arises when the kinetic coefficient of friction decreases as the relative velocity between two contacting surfaces increases, which makes the effective damping of the system negative. (1, 2). The mode-coupling phenomenon occurs when there are multiple modes whose natural frequencies are nearly identical (3–5). Such modes interact with one another to make the friction force produce a net positive energy into the system, developing the system instability. A sprag-slip mechanism, also known as geometrically induced instability or kinematic constraint instability, develops the system instability when certain geometrical conditions are satisfied. The sprag-slip mechanism can make the system unstable even when the kinetic coefficient of friction is constant (6, 7).

It is not possible to eliminate sliding contacts completely in a vehicle that has a very large number of structural parts and is subjected to a wide range of dynamic loading. A good structural design will not completely eliminate but minimize occurrence of sliding contacts. Hence, the approach should be identify potential contact areas in the design stage, and select a material pair that has a very low squeak propensity. A material database of squeak propensity will be necessary to enable such an approach. A novel, unique squeak test apparatus was developed in this work by utilizing a modified sprag-slip mechanism. The mechanism generates unstable friction-induced vibration in a highly consistent manner, enabling to measure squeak propensity of a given pair of materials. The device we developed can be used with an automatic detection and rating algorithm that was previously developed by authors to build material database.

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This paper reports the analysis and design part of the development of the test apparatus. The equation of motion of the system was developed and solved numerically to understand dynamics characteristics of the test apparatus. By using the test apparatus, motions and sounds were measured for several pairs of materials as demonstrations. It is demonstrated that squeak propensity of a materials pair can be assessed quantitatively by applying the automatic detection and rating algorithm and the test apparatus.

2. ANALYTICAL MODEL OF A SQUEAK TEST APPARATUS

An analytical model that describes the squeak test apparatus (Figure 1(c)) is shown in Figure 1(a). A rigid bar contacts with the bottom surface that moves to the left at constant velocity \( V \) with an angle of attack \( \theta_a \). Its other end is connected to a torsional spring \( (K) \) and a linear spring \( (k) \) that slides up and down along a frictionless guide which represents the compliance of the test apparatus. This analytical model is a single-degree-of-freedom system since the linear displacement at the end of the bar \( (y) \) is a function of the angular displacement of the bar \( (\theta) \).

![Figure 1](image_url)

**Figure 1** – (a) An analytical model of the squeak test apparatus designed, (b) the free body diagram of the model and (c) the picture of the test apparatus

From the free body diagram of the analytical model shown in Figure 1(b), the moment equation about the center of gravity of the rigid bar \( (G) \) becomes

\[
\sum M_G = -K\theta - ky \frac{l}{2} \sin \theta - F_s \frac{l}{2} \sin \theta - F_t \frac{l}{2} \cos \theta - F_n \frac{l}{2} \cos \theta = I_G \ddot{\theta} = I_G
\]  

(1)

The reaction force at the frictionless guide \( (F_s) \) and at the point of contact \( (F_n) \) can be obtained from the force equation in \( x \)- and \( y \)-direction as follows.

\[
F_s = ky - \frac{m}{2} \ddot{\theta} \sin \theta
\]  

(2)

\[
F_n = F_t + \frac{m}{2} \ddot{\theta} \cos \theta = \mu F_s + \frac{m}{2} \ddot{\theta} \cos \theta
\]  

(3)

\( y \) can be represented as;
By substituting Equation (2) through (4) into Equation (1), the equation of motion of the system is obtained as follows.

\[
y = l \left( \cos \theta_a - \cos \theta_r \right)
\]  

(4)

By substituting Equation (2) through (4) into Equation (1), the equation of motion of the system is obtained as follows.

\[
\left[ I_G + \frac{ml^2}{4} \left( 1 - \mu \sin 2 \theta_r \right) \right] \dot{\theta}_r + K \left( \theta_r - \theta_a \right) + kl^2 \left( \cos \theta_a - \cos \theta_r \right) \left( \sin \theta_r - \mu \cos \theta_r \right) = 0
\]  

(5)

where \( m \), \( I_G \), and \( l \) are the mass of the rigid bar, the moment of inertia of the rigid bar about its center of gravity, and the length of the rigid bar, respectively, and \( \mu \) is the kinetic coefficient of friction.

Equation (5) can be transformed to the state space equation as shown in Equation (6) by using state variables, \( x_1 = \theta_r \), \( x_2 = \dot{\theta}_r \).

\[
\begin{align*}
\dot{x}_1 &= \dot{\theta}_r = x_2 \\
\dot{x}_2 &= \ddot{\theta}_r = \frac{K \left( \theta_r - x_1 \right) + kl^2 \left( \cos x_1 - \cos \theta_a \right) \left( \sin x_1 - \mu \cos x_1 \right)}{I_G + \frac{ml^2}{4} \left( 1 - \mu \sin 2 x_1 \right)}
\end{align*}
\]  

(6)

Equation (6) is numerically integrated by using the 4th order Runge-Kutta method to obtain the transient response of the system.

Figure 2 shows the unstable responses of the system with \( m = 0.1 \) kg, \( l = 0.2 \) m, \( I_G = ml^2/12 \), \( k = 1 \times 10^5 \) N/m, \( K = 10 \times 10^2 \) N·m/rad, and \( \mu = 0.5 \). The amplitude of the response becomes bigger and unbounded, which means that the system becomes unstable.

![Figure 2](image)

Figure 2 – Transient responses of the analytical model. (a) angular displacement and (b) angular velocity.

3. MATERIAL PAIR TESTING

By using the squeak test apparatus that is shown in Figure 1(c), testing was conducted with four materials; aluminum and three polymers. As shown in Figure 3, an accelerometer was attached at the free-end of the thin beam to measure the acceleration during the test. The specimen at the bottom
rotates at a constant angular velocity controlled by a computer. The sound pressure of the generated noises was measured by a microphone which was located at 10 cm from the point of contact between the specimens. Three pairs of materials, which are aluminum-polymer A, aluminum-polymer B, and aluminum-polymer C, were tested to demonstrate the capability of the test apparatus to generate squeak noises.

![Experimental setup for material pair testing](image)

Figure 3 – Experimental setup for material pair testing

Figure 4 shows the measured time histories of the acceleration and the sound pressure of the generated from three different pairs of materials. The acceleration and sound pressure level periodically grow to very large amplitude and recede, showing that the motion of the system becomes unstable periodically.

![Figure 4](image)

Figure 4 – Measured time history of the acceleration and sound pressure of generated squeak noises. (a) aluminum-polymer A, (b) aluminum-polymer B and (c) aluminum-polymer C.
The objective rating of the generated squeak noises can be obtained by applying the automatic detection and rating algorithm (8, 9) that was previously developed by the authors. Figure 5 shows typical rating results. The algorithm to detect and rate squeak and rattle noises was developed by using wavelet based signal processing technique and psychoacoustic metrics. Based on the rating of the generated squeak noise shown in Figures 5, numerical squeak propensities of the three pairs are rated as 5.3, 13.5, 9.2, which are taken as the average of the peaks in the rating curves shown in Figure 5. Ratings of commonly used materials can be obtained for each combination and a material database can be developed.

![Figure 5](image_url)

Figure 5 – Objective rating of the generated squeak noises. (a) aluminum-polymer A pair, (b) aluminum-polymer B pair and (c) aluminum-polymer C pair.

4. DISCUSSION AND CONCLUSIONS

An analytical model of the squeak test apparatus developed based on the modified sprag-slip mechanism was developed to guide design of the apparatus. The equations of motion of the analytical model were solved numerically to obtain transient responses of the system testing a pair of materials. The results illustrates that the response grows unbounded for most pairs of materials, which means that system becomes unstable, hence, the squeak noise will be generated.

In order to confirm the capability of the test apparatus, three pairs of materials were tested, and induced motions and sounds were measured. Measured accelerations clearly show the device onsets of unstable motions with very large amplitude that generate loud transient noises. The automatic detection and rating algorithm for squeak and rattle noises developed by the authors was applied to obtain the ratings of generated squeak noises.

A difficulty in squeak test is consistency of the test. For example, if a pair of test materials squeaks on-and-off, generating completely different noises each time of testing, squeak propensity of the pair will not be able to be defined. The test apparatus developed in this work can generate squeak noises very consistently, making nearly the same squeak noises for the given pair in all tests. By combining the squeak test apparatus and the automatic detection and rating algorithm for squeak and rattle noises, objective rating of squeak propensity of any given material pairs becomes possible. The method and test apparatus developed will enable to build a database for automotive NVH engineers who work on squeak problems.

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