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Identification of vehicle suspension shock absorber squeak and rattle noise based on wavelet packet transforms and a genetic algorithm-support vector machine

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ABSTRACT

The squeak and rattle (S&R) noise of a vehicle's suspension shock absorber substantially influences the psychological and physiological perception of passengers. In this paper, a state-of-the-art method, specifically, a genetic algorithm-optimized support vector machine (GA-SVM), which can select the most effective feature subsets and optimize the model's free parameters, is proposed to identify this specific noise. A vehicular road test and a shock absorber rig test are conducted to investigate the relationship between these features, and then an approach for quantifying the shock absorber S&R noise is given. Pre-processed signals are decomposed through a wavelet packet transform (WPT), and two criteria, namely, the wavelet packet energy (WPE) and wavelet packet sample entropy (WPSE), are introduced as the feature extraction methods. Then, the two extracted feature sets are compared based on this genetic algorithm. Another advanced method, known as the genetic algorithm-optimized back propagation neural network (GA-BPNN), is introduced for comparison to illustrate the superiority of the newly developed GA-SVM model. The result shows that the WPSE can extract more useful features than the WPE and that the GA-SVM is more effective and efficient than the GA-BPNN. The proposed approach could be retrained and extended to address other fault identification problems.

1. Introduction

Vehicle noise, vibration and harshness (NVH) is very important to a customer's perception of vehicle quality. Therefore, much effort is invested in improving car riding comfort and interior sound quality [1]. However, as the main sound and vibration sources have been increasingly well controlled, other types of noise from previously ignored components, such as gear noise [2], heating, ventilation, and air conditioning (HVAC) noise [3], and wiper noise [4], have become prevalent. Among these numerous component noises, suspension shock absorber squeak and rattle (S&R) noise has been subject to increasing awareness from vehicular passengers.

The suspension shock absorber, which serves as the primarily stressed component, inevitably leads to shock and vibration and thus causes intensive noise during functioning. The so-called suspension shock absorber S&R noise is a structure-borne sound that is induced by the suspension shock absorber acting on the car body [5,6]. Specifically, when the internal components of the suspension shock absorber are resonating, the road excitation force is magnified and acts on the car body through the piston rod system of the shock absorber, which creates S&R noise [7]. This distinctive sound worsens when the car is driving on a bumpy road [8]. Identifying a vehicle's suspension shock absorber S&R noise is essential and realistic for the following three reasons. First, S&R noise weakens the interior sound quality of the vehicle and negatively affects the passengers' psychology and physiology. Second, this specific noise can worsen an automobile brand's image, increase the return rate, and raise the costs of vehicle and component companies. Third, although the structural design of the suspension shock absorber is satisfied, biases and inconsistencies still exist in manufacturing; as a result, some mass-produced shock absorbers can induce S&R noise.

The identification of vehicular suspension shock absorber S&R noise formerly depended on the subjective evaluation of a vehicular road test because this noise can be identified within the limits of human hearing perception. Some vehicular road studies found that S&R noise is related to the vibration characteristics of the car body at the locations where shock absorbers are assembled

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[9,10]. However, conducting a large number of vehicular road tests to identify S&R noise requires cooperation between motor companies and the automobile parts companies, which largely increases the manpower and cost of the car. Conversely, a rig test for suspension shock absorber S&R noise can overcome the disadvantages of requisite vehicular road tests. In one study, a quarter-car suspension system was used to investigate the S&R noise of a shock absorber and found that powerful impact acceleration along a shock absorber resulted in an intensive vibration of the car body, which can create a high S&R noise level [11]. Meanwhile, reports in the literature [8,12] have shown similar results. The methods used to extract the S&R characteristics and establish the relationships between the obtained features and human hearing perception are key factors in the identification of S&R noise. Although some researchers and engineers have engaged in developing means of identifying the S&R noise problem [13], few methods have been generally applied in industry. Therefore, a practical and state-of-the-art method for shock absorber S&R noise identification on a test rig, that also has a high correlation relationship with the subjective evaluation in a vehicular road test, is urgently needed in automobile engineering.

Extracting the S&R characteristics is essential to identify the precise identification of the associated S&R noise of a shock absorber. Some advanced time-frequency analysis techniques, such as the short time Fourier transform (STFT), Wigner-Ville distribution (WVD), empirical mode decomposition (EMD), wavelet transform (WT) and wavelet packet transform (WPT), have been widely used in sound and vibration signal processing to extract features from signals. Each of these methods has its own advantages and drawbacks. Compared to the STFT, the WT and WPT can process a signal using a variable resolution window rather than a fixed resolution window, but a wavelet function should be pre-defined [14]. The WVD is a special type of bilinear time-frequency transform that can provide the instantaneous power spectrum density of a signal, but the cross-terms will seriously affect its performance; therefore, the pseudo Wigner-Ville distribution (PWVD) and the smoothed pseudo Wigner-Ville distribution (SPWVD) have been proposed to suppress the influence of these cross-terms [15]. EMD is the kernel algorithm of the Hilbert-Huang transform (HHT), which can adaptively decompose a signal to several intrinsic mode functions (IMF) according to its own characteristics, but the decomposed IMF results in frequency overlap and is easily influenced by noise; hence, the ensemble empirical mode decomposition (EEMD) approach has been developed to solve these problems [16]. However, in practical use, few signal processing methods perform overwhelmingly better than others. Therefore, the method that should be selected mainly depends on the characteristics of an original signal and the purpose of the analysis.

Intelligent recognition methods should be considered to simulate the human auditory system because of the complexity of the human perception process. The artificial neural network (ANN), support vector machine (SVM) and multiple linear regression (MLR) approaches have been frequently mentioned in the literature [17,18]. Based on extensive empirical research, the ANN and SVM techniques have proven to be very powerful tools to map the nonlinear characteristics between the input features and the output targets, compared to the traditional MLR method [18]. The general parameters and hyper parameters of those models should be carefully selected to obtain satisfactory performance. However, no appropriate theoretical method exists to guide parameter selection. An advanced intelligent optimization algorithm should be introduced because of the irregularity of the parameter selection process. The genetic algorithm (GA), particle swarm optimization (PSO) and simulated annealing algorithm (SAA) are excellent methods to solve the nonlinear and multi-extremum programming in a broad range of research fields [19,20]. Therefore, a combination of an intelligent recognition method and an intelligent optimization algorithm should adequately quantify the S&R noise level of a vehicle's suspension shock absorber.

From the above descriptions, the pattern identification methods show a trend in development from traditional to intelligent approaches. In particular, the methods for S&R noise feature extraction and S&R noise pattern recognition must be carefully designed to identify shock absorber S&R noise. In this work, a new identification approach that combines the WPT and GA optimized SVM (GA-SVM) is proposed to detect the S&R noise of a vehicle's suspension shock absorber and is validated based on a vehicular road test and shock absorber test rig. The scheme of this research is presented in Fig. 1.

2. Theory background

2.1. Wavelet packet transform

Compared with the STFT, the WT can provide a varying time and frequency resolution when used in signal processing. However, this resolution is an equal exponential frequency partition [21] and decreases with increasing frequency. This shortcoming can sometimes reduce the accuracy when analyzing strong nonstationary or transient signals. The WPT is proposed to acquire more useful information. The WPT can offer a more detailed and adjustable resolution according to the characteristics and requirements of the signal [22]. Similar to the WT, the WPT can decompose a signal into an approximation coefficient and a detail coefficient. However, in contrast to the WT, the WPT can then split the detail coefficient into another approximation coefficient and another detail coefficient. An example of a 4-level decomposition tree for the WT and WPT is presented in Fig. 2, where x is the original signal, L is a low-pass filter, and H is a high-pass filter.

Theoretically, given the scaling function $\varphi(t)$ and the wavelet function $\psi(t)$, which are defined as $u_0(t) = \varphi(t)$ and $u_1(t) = \psi(t)$, the recursion equation of a wavelet packet is derived as follows:

$$\begin{cases} u_{2n}(t) = \sqrt{2}\sum_k h_k u_n(2t-k) \\ u_{2n+1}(t) = \sqrt{2}\sum_k g_k u_n(2t-k) \end{cases} \tag{1}$$

where h_k and g_k are the coefficients of the low-pass filter and the high-pass filter, respectively. Given an original signal $x(t)$ as $C^{0,0}$, the decomposed approximation coefficient and detail coefficient of the WPT can be obtained by

$$\begin{cases} C_m^{j,2n} = \sum_{k=-\infty}^{\infty} h^*_{2m-k} C_k^{j+1,n} \\ C_m^{j,2n+1} = \sum_{k=-\infty}^{\infty} g^*_{2m-k} C_k^{j+1,n} \end{cases} \tag{2}$$

where j, m and n are the scale, translation and oscillation parameters, respectively. Thus, the completed WPT can be achieved via Eq. (3).

Meanwhile, the reconstruction of the WPT coefficients is defined as

$$C_m^{j+1,n} = \sum_{k=-\infty}^{\infty} h_{2m-k} C_k^{j,2n} + \sum_{k=-\infty}^{\infty} g_{2m-k} C_k^{j,2n+1} \tag{3}$$

2.2. Genetic algorithm-support vector machine

2.2.1. Support vector machine

SVMs were first proposed by Vapnik in 1995 [23] and have been demonstrated to be a very powerful tool for solving regression,