

An Indirect TPMS Algorithm Based on Tire Resonance Frequency Estimated by AR Model

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ABSTRACT

Proper tire pressure is very important for multiple driving performance of a car, and it is necessary to monitor and warn the abnormal tire pressure online. Indirect Tire Pressure Monitoring System (TPMS) monitors the tire pressure based on the wheel speed signals of Anti-lock Braking System (ABS). In this paper, an indirect TPMS method is proposed to estimate the tire pressure according to its resonance frequency of circumferential vibration. Firstly, the errors of ABS wheel speed sensor system caused by the machining tolerance of the tooth ring are estimated based on the measured wheel speed using Recursive Least Squares (RLS) algorithm and the measuring errors are eliminated from the wheel speed signal. Then, the data segments with drive train torsional vibration are found out and eliminated by the methods of correlation analysis. Using the corrected and selected vibration noise, the resonance frequency of the tire vibration system is identified by Maximum Entropy Spectral Estimation (MESE) based on Auto-regressive (AR) model. Finally, the proposed algorithm is verified by test data, and the results show that the resonance frequency can be estimated and the changing of tire pressure can be indicated consequently.

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INTRODUCTION

As is well known, the improper tire pressure might result in serious wear of tires and high fuel consumption of cars. More seriously, deflated tires are more likely to be blown out and result in severe accidents [1]. Therefore, the study of Tire Pressure Monitoring System (TPMS), which is designed to monitor and warn the abnormal tire pressure online, is necessary for accident prevention of motor vehicles. In some applications which are named as direct TPMS, tire pressure can be measured directly by pressure sensors mounted inside of the tire or on the inflating valve [2][3]. More economically, tire pressure can be monitored by some kinds of indirect signals and algorithms, and these applications are named as indirect TPMS [4]. In these applications, additional sensors are not necessary and ABS wheel speed signals are used to identify tire pressures according to specific tire characteristics. For instance, rolling radius of a tire will change along with its pressure, which will further result in changes of vehicle states. Thus, the low tire pressure can be monitored by different kinds of vehicle state observers [5][6]. This method works effectively except when all of the tires of a car are deflated to the same pressure, which means the sizes of tires are almost equal and the difference between tire radii cannot be observed [1]. Another application of indirectly TPMS is based on the characteristic between the tire resonance frequency and its pressure. Normally, the higher the tire pressure is, the larger its resonance frequency is. As this method is based on the characteristic of each tire itself, the pressure of a specific tire can be monitored independently, and thus, deflations of any tires can be monitored.

In the frequency based TPMS methods, the tire is look as a vibration system around its circumference, and the noise in wheel speed signal is the response of the vibration system under the excitation of road irregularity. Assuming the road input to be white noise, the resonance frequency of the tire system can be monitored by spectrum analysis methods, and the tire pressure can be estimated consequently. Although there have been plenty of researches about indirect TPMS, the studies on how to improve the accuracy and operating speed of the algorithm are always necessary.

The first essential issue is to find out "effective" data from ABS wheel speed signals. In order to identify the resonance frequency of a tire, the excitation of the tire vibration system must be "good" white noise. If there exist too many disturbances in the excitations, the resonance frequency cannot be identified accurately. The disturbances might be caused by excitation of road, system error of measuring system or torsional vibration of powertrain. That is why the frequency based TPMS won't work when the car is driving on rough road or the torsional vibration is happening in drive line. In this paper, we tried to find out ways to eliminate the "bad" vibration data for tire resonance frequency identification. The manufacturing error of the tooth ring and the drive line torsional vibration are analyzed, estimated and eliminated from the ABS wheel speed signals.

Another important issue in tire resonance frequency identification is the spectrum analysis methods. In the past decades, various spectrum analysis methods are utilized in these TPMS algorithms and the Fast Fourier Transform (FFT) is the most widely used one [7]. The

wavelet based methods are also used in time-frequency analysis of the characteristic between tire resonance frequency and wheel speed signals [8][9]. Comparing to these methods, the Maximum Entropy Spectral Estimation (MESE) method based on Auto-Regressive (AR) model has higher resolution than FFT and smaller computational complexity than wavelet, and might show good performance in tire resonance frequency identification [12]. In this paper, the AR based MESE algorithm is designed to achieve better performance of resonance frequency estimation.

In this paper, a frequency-analysis based Indirect TPMS is researched to monitor tire pressure more accurately. This paper is organized as follows:

1. The ABS wheel speed was analyzed, and the manufacturing error of the ABS tooth ring is identified. Based on this, the effect caused by the manufacturing error is eliminated from the measured wheel speed signals.
2. Based on the corrected signals, the correlations of the speeds of driving wheel are analyzed. The data segments which show drive line torsional vibration won't be used in the following spectrum estimation.
3. Then, the AR model is established and the MESE method is used to identify the tire resonance frequency and estimate the tire pressure deflation.

Finally, the proposed algorithm is verified by test data samples, and the statistic of these samples is described.

IDENTIFICATION OF TOOTH RING ERROR OF ABS WHEEL SPEED SENSOR

The wheel speed sensor system is one of the most important components of ABS. It is consisted of a toothed ring and an electromagnetic sensor, which is shown in Figure 1. It measures the time span when each tooth rotationally passes over the electromagnetic sensor, and then the wheel rotational speed can be calculated according to the time spans. For the estimation of tire resonance frequency, the vibration noise in wheel speed should be extracted and analyzed by frequency-domain method such as FFT.

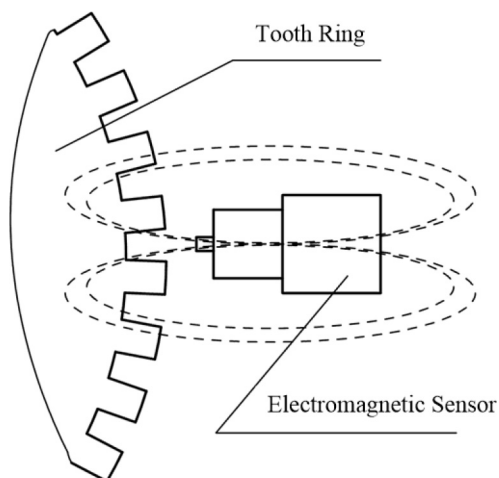


Figure 1. The ABS wheel speed sensor system

A 2Hz high-pass filter is used to filter the wheel speed signals to acquire the vibration noise, and the noise is further analyzed by FFT. Figure 2 is the waterfall plot of the original wheel vibration noise spectrum maps. Due to large differences of the magnitudes of the spectrum on different frequency segments, the energy concentration on frequency domain cannot be seen clearly.

Figure 3 is the 2D version of waterfall in Figure 2. In Figure 3, each line is a PSD map based on a noise data which is measured at a constant vehicle speed. The vehicle speed is shown on the y-axis, and the spectrum maps are plotted on their corresponding vehicle speed. As the magnitudes of spectrums are too small to be distinguished in comparison with vehicle speed, they are magnified 100 times. It is clear that there exist peaks relative to vehicle speed. However, the tire resonance frequency should be actually insensitive to vehicle speed. It means that these peaks are caused by some other disturbances.

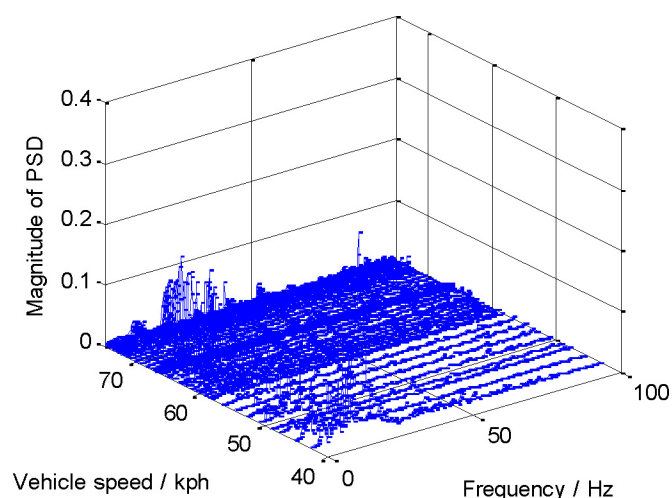


Figure 2. The waterfall plot of original wheel speed noise

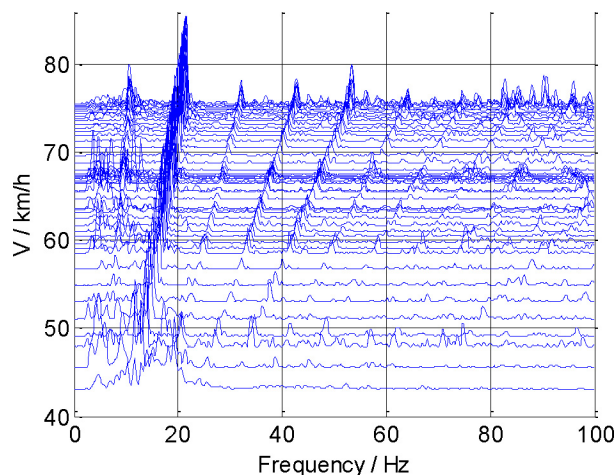


Figure 3. The 2D waterfall plot of original wheel speed noise

Ideally, the teeth should be equally spaced around the circumference of the ring. However, manufacturing error and deformation error, which should be considered as systemic errors of the wheel speed measuring system, exist on each tooth. These errors are not problems for the usage, such as in ABS or ESP control, because the noises caused by them are much smaller than wheel speed. But as shown in

Figure 3, the peaks that might depict tire resonance frequency cannot be seen at all. That means these errors cannot be ignored as their magnitudes are equivalent to the vibration noise of wheel speed. They must be identified and eliminated before estimating the tire resonance frequency precisely.

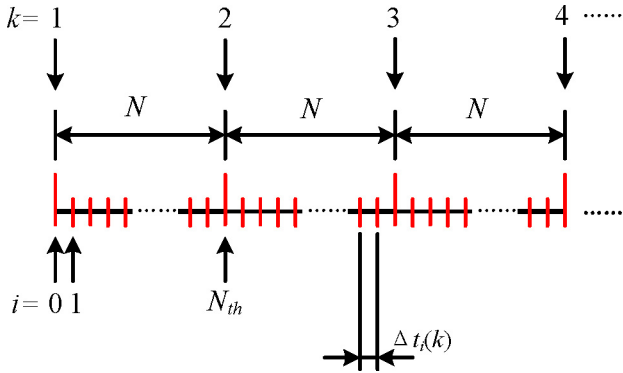


Figure 4. Time spans of teeth rotation

For a toothed ring with N_t teeth, N_t time spans will be logged per rotation. As shown in Figure 4, let the number of rotation circles be k and the number of teeth be i , and mark the time span of the i th tooth in the k th circle as $\Delta t_i(k)$.

All of the logged $\Delta t_i(k)$ will compose a data series which can be used to identify the error of the i th tooth.

To identify the error of the toothed ring, the linear error model is established [10]. The measured value of the k th error of the i th tooth is

$$\Delta \theta_i(k) = \theta_i(k) - \theta_0 \quad (1)$$

Where,

$$\theta_i(k) = \bar{\omega}(k) \Delta t_i(k) \quad (2)$$

$$\theta_0 = \frac{2\pi}{N_t} \quad (3)$$

$\bar{\omega}(k)$ is the average rotational speed of one circle

$$\bar{\omega}(k) = \frac{2\pi}{\sum_{m=k-N_t+1}^k \Delta t_i(m)} \quad (4)$$

In this paper, Recursive Least Squares (RLS) algorithm is used to identify the errors. Let the estimated value of the k th error of the i th tooth is $\Delta \hat{\theta}_i(k)$, the error between the estimated and measured value should be

$$\Delta \tilde{\theta}_i(k) = \Delta \hat{\theta}_i(k-1) - \Delta \theta_i(k) \quad (5)$$

$\Delta \hat{\theta}_i(k)$ can be updated recursively by the following steps [11]

$$q(k) = \frac{p(k-1)}{\lambda + p(k-1)} \quad (6)$$

$$\Delta \hat{\theta}_i(k) = \Delta \hat{\theta}_i(k-1) + q(k) \Delta \tilde{\theta}_i(k) \quad (7)$$

$$p(k) = (1 - q(k)) p(k-1) \quad (8)$$

Where p is recursive factor with $p(1) = 1$, λ is the forgetting factor and $\lambda \in (0, 1]$.

The flow chart of the estimation algorithm of teeth errors is shown in Figure 5. The manufacturing error of a qualified tooth ring product cannot exceed its designed tolerance requirement. The situation that the measured $\Delta \theta$ exceed the tolerance restriction might be caused by sharp acceleration or deceleration of the vehicle and the average wheel speed $\bar{\omega}$ is not accurate. Thus, the recursive procedure should not be started until the initial value $\Delta \hat{\theta}_i(1)$ falls into its tolerance restriction region.

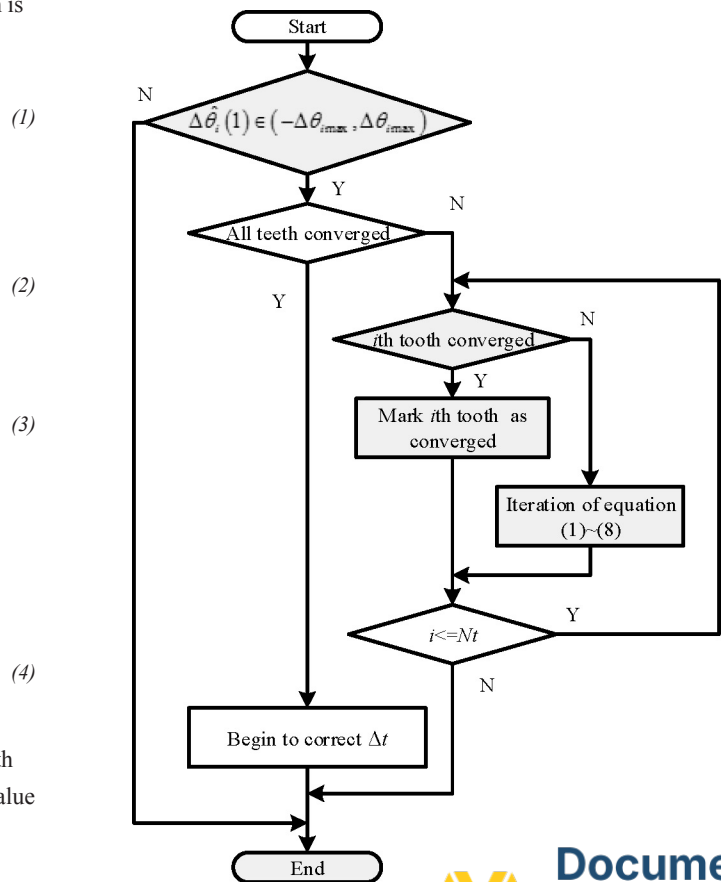


Figure 5. Flow chart of teeth errors estimation