American Journal of Mechanical Engineering, 2014, Vol. 2, No. 3, 54-57
Available online at http://pubs.sciepub.com/ajme/2/3/1

DOI:10.12691/ajme-2-3-1

Research on Real-time Identification for Tire Failure

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Received April 08, 2014; Revised May 04, 2014; Accepted May 07, 2014

Abstract Sudden tire failure (a blowout) is a major cause of traffic accidents, many of them involving fatalities. If the automobile can quickly identify that a blowout has occurred, the braking system can be programmed to carry out braking and stability control to slow down the vehicle steadily. Hence, timely identification of a blowout or severe leakage is a key enabler of using the braking system to provide control and stability enhancements in the event of a tire failure. This work presents an indirect real-time monitoring strategy that combines analysis of tire vibration with effective radius, to indicate that a blowout has occurred. The calibrating and related test results show that the system can detect tire blow-out timely and accurately.

Keywords: *tire blowout or severe leakage, real-time identification, tire vibration, effective radius, test set*

Cite This Article: Qingzhang Chen, Jonathan M. Weaver, and Guangju Xu, "Research on Real-time Identification for Tire Failure." *American Journal of Mechanical Engineering*, vol. 2, no. 3 (2014): 54-57. doi: 10.12691/ajme-2-3-1.

1. Introduction

Tire blowout or severe leakage significantly affects the vehicle dynamic characteristics. The driver's response sometimes results in severe side slip, lateral drift, or even overturning of the vehicle [1,2,3].

It can be difficult for a driver to quickly sense that a blowout has occurred. This is due to the driver focus being elsewhere, sound insulation of the vehicle isolating them from the audible effects, and the noise of vehicle itself [4]. Studies show that the handling performance of the vehicle changes little within 2 to 3 seconds after a blowout, making that the best time to lower speed and maintain stability of the vehicle, and the speed can be reduced to a safe range only if properly operated [5,6]. Hence, real-time identification of a blowout is a key step in improving the stability and control following a tire blowout.

An indirect real-time monitoring method that combines analysis of tire vibration and effective radius is provided herein. This work shows that such a system can identify a blowout condition within approximately 0.6 seconds, implying that the emergency braking system could be programmed to provided an automated response to the blowout to safely and controllably slow the vehicle to a safe speed.

2. System Principle

Figure 1 shows a schematic of the proposed system. The system utilizes the wheel speed signal. The resonance frequency is determined by frequency analysis and the effective tire radius is calculated based on the wheel speed information. On the basis of empirical formula and experiments, the correlation thresholds (or criterion) for tire blowout or severe leakage are determined. If the characteristic of the tire frequency or radius is in the range of the established criteria, then a weighted factor analysis is used to determine if the target tire has experienced a blowout or severe leakage. Ultimately, if a blowout is determined, an emergency automotive braking system response is initiated.

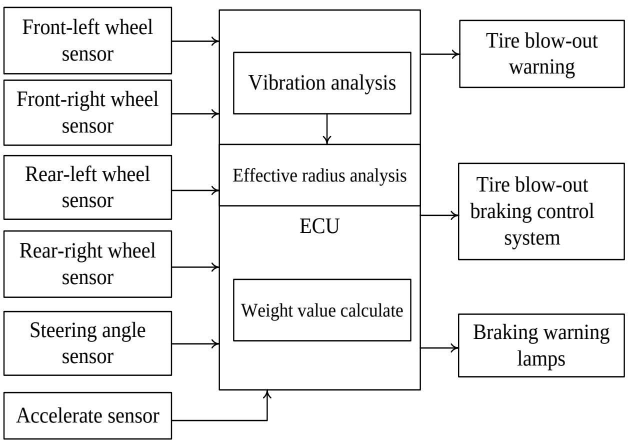


Figure 1. System schematic

3. Vibration Analysis

Each wheel speed signal is sent to the ECU (Electronic Controlling Unit) where the vibration analysis is carried out as follows:

Firstly, the threshold of resonance frequency for tire blowout or severe leakage is calculated, according to an empirical relation formula between the torsional elastic stiffness and natural frequency of tire, as follows [7]:

$$f_{resonance} = \frac{1}{2\pi}\sqrt{\frac{k-\Delta k}{N_i}} \quad (1)$$

In formula (1), $f_{resonance}$ is tire resonance frequency, k is the torsional elastic stiffness, Δk is the variation of k, N_i is the normal force acting on the tire, $i = FL, FR, RL, RR$ (Means Front Left, Front Right, Rear Left, Rear Right wheel respectively). The stiffness k is changing in direct proportion with the pressure in the simplified tire model. We define that it is a blowout or severe leakage when the tire pressure is lower than 50% of nominal, then the resonance frequency can be expressed as follows [8]:

$$f_{resonance-\min} = \frac{1}{2\pi}\sqrt{\frac{2k_0}{G}} \quad (2)$$

In expression (2), $f_{resonance-\min}$ is the threshold of tire natural frequency, k_0 is the torsional elastic stiffness under normal tire pressure and it can be measured by static measurement, G is the vehicle weight (we assume equal static weight distribution).

The wheel speed time domain signal is transformed into frequency domain with Fast Fourier Transform (FFT) to get the corresponding real-time resonance frequency, named $f_{resonance-real}$, as follows:

Discrete Fourier Transform (DFT) is calculated with FFT, defining a DFT of x sequence with length N [9]:

$$\begin{gathered} X(n) = \sum_{k=0}^{N-1} x(k) e^{-i\frac{2\pi n}{N}k} \\ x(k) = \frac{1}{N}\sum_{k=0}^{N-1} X(n) e^{i\frac{2\pi k}{N}n} \\ k, n = 0, 1, ..., N-1 \end{gathered} \quad (3)$$

If the sampling period of the wheel speed signal $x(k)$ is T_s, then the corresponding frequencies of $X(n)$ is $f(n) = n / NT_s$. The calculation of resonance frequency is as follows:

$$\begin{gathered} \hat{n} = \underset{n\in[0,N-1]}{\arg} \max |X(n)|^2 \\ f_{resonance-real} = f(\hat{n}) = \frac{\hat{n}}{NT_s} \end{gathered} \quad (4)$$

In expression (4), $\hat{n}$ is the estimated speed rate, if $f_{resonance-real} \le f_{resonance-\min}$ in a tire, then the real-time resonance frequency is corrected by weight according to vehicle turning, accelerating and decelerating conditions, the weight value t_i is relating to steering direction, turning radius, severity of braking, and acceleration (grade is neglected herein but could also be included). To simplify algorithm, the weight value is defined as $t_i = 1$ when the vertical load is increasing on the detected abnormal wheel due to steering, braking and accelerating is less than $0.25G$ (which is approximately 1 time of original load), and if the load increase is greater than $0.25G$, then $t_i = 0.8$. If $t_i \cdot f_{resonance-real} \le f_{resonance-\min}$ is true, then one of the necessary conditions of tire blowout or severe leakage is determined, and further analysis is carried out according to effective radius.

4. Effective Radius Analysis

Due to large deformation of the tire when blowing out or experiencing severe leakage, the effective wheel radius is rapidly decreasing. According to relevant technical literature data, we suppose that if the deformation of tire is more than half of tire height (h_{tire}) within 200ms, then blowout or severe leakage is likely happening on the tire. If the change rate of wheel speed (ω'_j) in this period of time is larger than the threshold $\omega'_{j-\max}$ as per following expression, then one of the criterions for indicating tire blowout or severe leakage comes into being.

$$\omega'_j \ge \frac{h_{tire}}{2r - h_{tire}} = \omega'_{j-\max} \quad (5)$$

In expression (5), r is the wheel radius when the tire is at normal pressure. j means the target tire is judged to have a blow-out or severe leakage. If it is normal pressure in all tires, the ratio (η, the numerator includes wheel j) between the product of diagonal wheels radius is approximately one. When one of the tires is blown out or severely leaking, the effective radius change leads to a change in η, and another criterion is expressed as follows:

$$\eta \ge \frac{r}{r - 0.5h_{tire}} = \eta_{\max} \quad (6)$$

If the above two criterions which derived from the effective radius analyzing are satisfied, then the target tire is determined to be have experienced a blowout or severe leakage.

If the criterions from the tire vibration and effective radius analysis are confirmed, then tire blowout or severe leakage is confirmed. This multi-criterion evaluation minimizes the possibility of a false positive (indicating a blowout or excessive leakage has occurred when it has not).

5. System Process and Calibration

The system software process is shown as Figure 2.

After completing the system hardware and software design, the matching and calibrating test is carried out for a target vehicle. The test equipment for tire blowout or severe leakage is designed as Figure 3. Note that there are eight exhausting holes drilled on the wheel rim. The holes connect with an exhausting control valve by soft-pipes which achieve gas leakage control, and different leakage intensity can be simulated by combining a different number of exhausting holes. The changes of tire natural frequency and effective radius at different leakage intensity are detected, and the $f_{resonance-\min}$, $\omega'_{j-\max}$, $\eta_{\max}$ are determined at different wheel loads. We define that it is a tire blowout when the combining exhausting holes number is at least four holes and severe leakage when the number is not more than four holes.

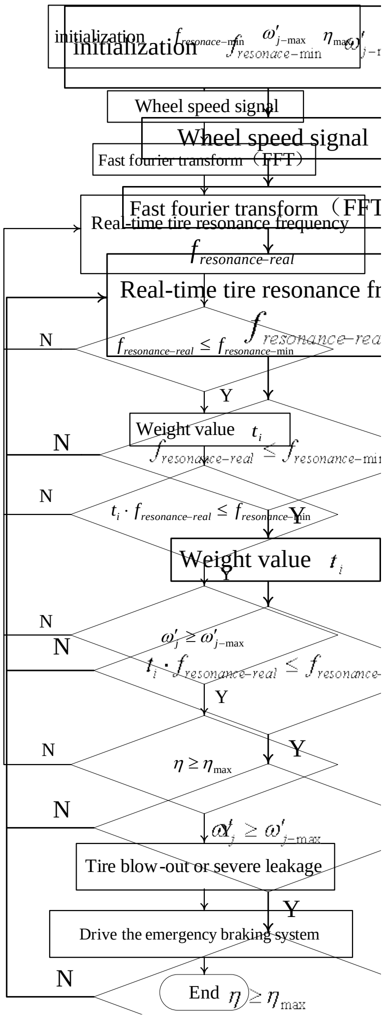
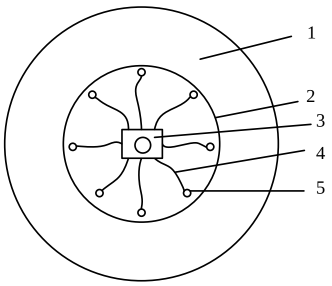


Figure 2. System software process



1-tire 2-wheel ring 3-deflate control valve

4-airway tube 5- release hole (a total of 8）

Figure 3. Test equipment

6. Test Results

The test is carried out on a BJ2500. The average air pressure of the tires is charged to normal (250kPa), and the testing ground is a flat cement road (a vehicle brake system testing ground of a company). The test equipment is controlled by a remote switch. The picture of road test set is shown as Figure 4. The tire blowout trigger signal (TBTS) which is produced by the remote switch and tire failure identify signal (TFIS) are collected by DL750 oscilloscope. With the TBTS and TFIS, we can find out whether the identification is efficient and the time response of the proposed tire failure identification system.

Figure 4. The picture of road test set

Table 1 shows the results of the test. 'Speed' in the table is vehicle speed. 'Test times' means the time of simulating tire blow-out repeatedly. 'Identify times' means the time identify of tire failure efficiently. 'Average time delay' means the average time delay for efficient identification.

Table 1. Test results

Speed (km/h)	Test times	Identify times	Average time delay (ms)
20	12	1	-
30	9	1	-
50	9	8	566
70	6	6	537
90	5	4	449

The test results show that it is efficient to detect tire blow-out with vehicle speed from 50km/h to 90km/h, and can detecting tire severe leakage efficiently only if when vehicle speed is at 50-90km/h. The system proved ineffective for speeds of 20 km/h and 30 km/h. The average time delay is far less than the 2 to 3 second typical driver response time, demonstrating that the tire failure identification system can save time for relative emergency braking system to carry out braking and stability controlling.

7. Conclusion

The dual criterion algorithm to determine when a tire blowout or excessive leakage has occurred is developed. This method combines frequency analysis with effective radius analysis to identify a blowout within approximately 0.6 seconds on a test vehicle between 50 km/h and 90 km/h. Additional work is needed to address challenges with higher speeds; specifically, higher wheel speed sampling rate would enable better detection. The system also did not respond well at lower speeds, but the danger under those speeds is significantly reduced compared to higher speeds.

Acknowledgement

This work was supported by 'The Natural Science Foundation' (BK2011367) and 'Six Peak Talents Foundation' (SZ2010002) of Jiangsu Province funded by the Chinese Government.

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