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Research on Fault Mechanism and Diagnosis Method of Automobile Abnormal Tire Wear

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Abstract: Tires are the only vehicle components in direct contact with the road surface. The contact state of the tire tread determines the vehicle dynamic characteristics, braking performance and driving stability. Different from uniform natural wear, abnormal tire wear is an external fault phenomenon induced by the coupling effects of tire inflation pressure, wheel alignment parameters, suspension-steering assemblies and wheel-edge dynamics. In practical maintenance, excessive reliance on wheel alignment calibration while ignoring the dynamic state of the chassis is common. Calibration alone often fails to eliminate dynamic abnormal wear and leads to repeated rework. Starting from tire contact mechanics, this paper categorizes typical wear morphologies including shoulder bias wear, feathered zigzag wear, cupped scallop wear and local patch wear. A hierarchical fault diagnosis framework is established following the workflow: wear feature identification, basic parameter verification, chassis clearance and deformation inspection, dynamic calibration and road test validation. A real-vehicle case is analyzed to interpret the diagnosis logic, and preventive maintenance strategies for the coupled suspension-tire system are proposed. This study can provide theoretical support and engineering reference for chassis fault diagnosis and vehicle chassis calibration.

Keywords: tire; abnormal wear; wheel alignment; suspension dynamics; fault diagnosis; contact patch

1. INTRODUCTION

Tire wear is essentially a fatigue abrasion process of tread rubber under combined slip friction and alternating contact pressure. Under ideal operating conditions, the contact pressure distribution within the tire contact patch remains uniform and the slip ratio is controlled within a reasonable range, resulting in even tread wear. Once system parameters deviate from the design range, local slip and periodic load pulsation will trigger various non-uniform wear forms, namely abnormal tire wear.

Foreign researchers have carried out early studies on semi-empirical tire wear models. Grosch systematically explained the friction and wear mechanism of rubber and pointed out that tread wear is strongly correlated with slip velocity, contact pressure and hysteresis characteristics of rubber. Sueoka et al. investigated polygonal and cupped tire wear from the perspective of vehicle dynamics and revealed that resonance between the natural frequency of suspension and circumferential tire excitation is the root cause of scallop wear. Veen further constructed an analytical model for dynamic irregular tire wear and verified that damping degradation of shock absorbers and increased bushing clearance cause periodic fluctuation of contact load and finally form scalloped wear patterns. Domestic research mainly focuses on hard-point optimization of suspension and matching of wheel alignment parameters. Systematic fault tracing research guided by wear morphology for maintenance scenarios still needs further enrichment.

Engineering practice proves that abnormal tire wear is not a failure caused by a single factor, but an external manifestation of coupled faults of chassis subsystems. Simply replacing tires or adjusting toe and camber angles cannot eliminate dynamic load disturbance induced by loose suspension joints or degraded damping performance, which inevitably results in recurring wear faults. Therefore, it is necessary to establish a mechanics-based hierarchical diagnosis system and distinguish static geometry-induced wear from dynamically excited wear, which has obvious engineering significance.

2. Mechanical Mechanism and Classification of Abnormal Tire Wear

The pressure distribution of the contact patch and micro-slip of tread blocks dominate wear morphology. According to excitation sources, abnormal tire wear is classified into four categories: wear induced by inflation pressure deviation, wear induced by wheel alignment misalignment, wear induced by degraded suspension dynamic performance, and wear induced by wheel assembly and brake system defects.

2.1 Wear caused by abnormal tire inflation pressure

Inflation pressure changes tire carcass stiffness and the shape of the contact patch. When inflation pressure exceeds the nominal value, the central crown region bears concentrated load, the contact area shrinks, and the wear rate of the tread crown is much higher than that of both shoulders. Under-inflation leads to repeated bending of the sidewall, and the load transfers to two shoulders, which preferentially wear out. This type of wear belongs to quasi-static load distribution failure; the circumferential wear is uniform without discrete local pits.

2.2 Wear caused by misaligned wheel alignment parameters

Toe angle and camber angle govern the lateral slip state of rolling tires. Deviated camber leads to continuous lateral load on one shoulder and causes inner or outer shoulder bias wear. Misadjusted toe angle introduces persistent lateral slip during wheel rolling, and one side of tread blocks is continuously scraped to form typical feathered wear. The sharp side of feathered patterns can be touched manually to judge whether the toe angle is excessive or insufficient. This is defined as

geometric wear. If no clearance exists in chassis components, it can generally be eliminated by wheel alignment calibration.

2.3 Dynamic wear induced by degraded suspension guiding and damping components

Damping attenuation of shock absorbers and excessive clearance of control arm bushings and ball joints are primary inducements of cupped wear. Under road excitation, insufficient suspension damping fails to attenuate wheel vertical vibration rapidly, the tire contact load fluctuates periodically, and local tread repeatedly impacts the road to form circumferentially discrete scalloped pits. This is dynamic wear. Its prominent feature is that static alignment parameters may fall within the qualified range, while wheel attitude continuously varies with vibration during driving. This explains why simple wheel alignment always fails for such faults.

2.4 Local patch wear induced by wheel and brake system defects

Rim deformation, severe wheel unbalance, excessive hub bearing clearance and brake drag result in sudden local load change or persistent sliding friction within one wheel rotation cycle, presenting as isolated patch wear, usually accompanied by wheel run-out and steering wheel shimmy at high speed.

3. Hierarchical Fault Diagnosis Framework

The diagnosis principle follows a sequence: from simple inspection to complex test, static check before dynamic test, and mechanical inspection prior to instrument calibration, to prevent instrument calibration from covering inherent mechanical defects of the chassis.

1.Wear feature recognition and working condition collection: Record collision and undercarriage impact history, identify wear morphology, preliminarily judge wear type (static geometric type / dynamic suspension type), measure tread depth, and compare wear difference between coaxial and diagonal tires.

2.Basic parameter verificatio: Adjust inflation pressure according to the vehicle certification label, verify the consistency of specification, load index and tread pattern of coaxial tires, and inspect brake drag and hub bearing preload.

3.Chassis mechanical inspection on lift (core procedure): Use pry bars to test clearance of control arm bushings, steering tie rod ball joints and stabilizer links. Inspect shock absorber leakage and plastic deformation of control arms and knuckles visually. Components with debonded bushings, out-of-tolerance ball joint clearance or degraded shock absorber damping must be replaced preferentially. If chassis joints have excessive clearance, wheel alignment parameters are time-variant and the calibrated result cannot maintain long-term validity.

4.Instrument calibration: After repairing all defective mechanical chassis parts, perform wheel balancing and four-wheel alignment to calibrate toe, camber, caster and kingpin inclination. For vehicles equipped with air suspension or steer-by-wire chassis, height sensor calibration must be completed before alignment inspection.

5.Road test verification and long-term tracking: Test straight-line stability, shimmy and abnormal noise on both smooth and bumpy roads. Monitor the evolution of tread wear for a period to confirm that the excitation source is removed.

4. Case Study of Fault Diagnosis

A front-wheel-drive passenger car with a mileage of 42,000 km suffered from scalloped cupped wear on two front tires and periodic chassis buzzing vibration above 80 km/h. In previous maintenance, new tires were installed and wheel alignment was adjusted. However, abnormal wear reappeared after 5,000 km.

1.Wear judgment: Discrete pits distributed on the tread indicated cupped wear excited by dynamic load pulsation. Suspension damping and joint clearance were prioritized for inspection.

2.Basic check: Inflation pressure conformed to factory specifications and no brake drag was detected.

3.Lift inspection: Oil leakage was found on the right-front shock absorber. After pressing and releasing the front fender, the body bounced more than three times, indicating obvious damping degradation. Cracks were observed on the lower control arm rubber bushing with minor free play.

4Mechanism analysis: The shock absorber failed to suppress vertical wheel vibration and induced periodic fluctuation of contact load; bushing clearance further amplified dynamic deviation of wheel attitude. Previous maintenance only corrected static geometric parameters without eliminating dynamic excitation, so the fault recurred.

5.Repair scheme: Replace shock absorber assemblies in pairs on the same axle and renew the lower control arm bushing. Tighten joint bolts according to the torque specified in service manuals.

6.Calibration and validation: Complete wheel dynamic balancing and four-wheel alignment. High-speed vibration disappeared after road test. Follow-up observation of 8,000 km showed uniform tread wear without secondary cupping.

The case demonstrates that feathered wear corresponds to toe misalignment, shoulder bias wear is mainly related to camber deviation and component deformation, and cupped wear is a signature fault of degraded suspension damping and loose joints. Wear morphology serves as critical input for fault tracing.

5. Common Diagnosis Pitfalls and Preventive Maintenance Strategy

5.1 Typical pitfalls in maintenance

(1) Attributing all tire bias wear to misaligned wheel alignment and skipping chassis clearance inspection;

(2) Directly replacing tires without tracing root failure causes;

(3) Mixing tires of different patterns on the same axle and introducing extra lateral slip;

(4) Conducting wheel alignment without height calibration for electronically controlled suspension vehicles, leading to distorted alignment reference.

5.2 Preventive maintenance

Check tire pressure periodically and rotate tires following the schedule in the owner manual. Avoid hitting curbs and potholes at high speed to prevent deformation of suspension hard points. After undercarriage collision, inspect suspension clearance and recheck alignment even without obvious

abnormal noise. Carry out wheel dynamic balancing every 20,000 km. Replace tires when tread depth reaches the wear limit of 1.6 mm. With the popularization of active suspension and steer-by-wire chassis, online early warning of tire wear based on vehicle vibration signals and steering angle data can be realized in future applications.

6. Conclusion

Abnormal tire wear is a comprehensive result coupled with tread tribology, wheel geometric alignment and suspension dynamics. Inflation pressure determines the overall shape of the contact patch. Alignment parameters such as toe and camber dominate static lateral slip and induce shoulder bias wear and feathered wear. Damping degradation of shock absorbers and excessive clearance of bushings and ball joints trigger pulsating contact load, which is the main inducement of dynamic cupped wear. Rim deformation and brake drag cause local patch wear.

The core of fault diagnosis is to distinguish static geometric excitation and dynamic dynamic excitation. Inspection of chassis joint clearance and damping performance must be conducted before wheel alignment. The hierarchical diagnosis workflow proposed in this paper can eliminate wear incentives from the source and reduce rework rate. Follow-up research can combine multi-body dynamic simulation to quantify the influence of alignment parameters, bushing stiffness and shock absorber damping on tire slip and wear rate, and establish a predictive wear model.

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