

Severity Analysis of m-LSD Differential Durability Test Using the ison Surface Fatigue Equation

- Pitting Fatigue Life Prediction and Test Mode Development Based on Vehicle Circuit Driving Data-

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The importance of active torque vectoring technology for cornering performance and traction assurance has grown significantly in high-performance vehicle development. Major automotive manufacturers in Germany, Japan, and Korea are actively implementing various differential control technologies in front-wheel-drive-based high-performance vehicles. Among these, the mechanical LSD (m-LSD) remains a key solution due to its cost-effectiveness and rapid mechanical response. In particular, single-motor-based front-wheel-drive high-performance EVs cannot electronically control the rotational speed difference between left and right drive shafts, making the role of m-LSD indispensable.

However, the asymmetric cam-ring gear structure inside m-LSD systems exhibits load transmission characteristics close to local point contact rather than line contact, making them susceptible to pitting fatigue damage at specific slip and high-load conditions. Therefore, establishing differential durability test conditions that quantitatively reflect real operating scenarios is essential.

This study aims to predict pitting fatigue life at the cam-ring contact interface by applying the Morrison fatigue life equation, and to propose a reliable durability test severity quantification methodology by quantitatively comparing accumulated contact fatigue damage between real vehicle circuit driving data and component-level bench testing.

Tangential load, normal load, friction energy, and bending stress acting on the cam gear contact surface were calculated from measured vehicle torque and rotational speed. The Morrison contact fatigue life equation is an empirical formula for predicting surface fatigue life of components experiencing localized Hertz contact stress, defined as follows:

$$N_p = 10^{\zeta - \lambda \cdot \log_{10}(K_{i,max})}$$

where N_p is the pitting fatigue life (cycles), ζ is the strength coefficient, λ is the material sensitivity coefficient, and K_i is the load stress factor at the cam-ring contact point. The cam-ring contact force F_i was calculated for each pinion contact point using input torque, effective contact radius, and pressure angle.

Drive shaft torque, rotational speed (RPM), and differential speed were measured on the Yeongam KIC full course (approximately 12 laps, 70 km) using GNSS, drive shaft torque sensors (500 Hz), vehicle CAN, and IMU. Corner-by-corner analysis using Python's geopy function extracted load characteristics, and accumulated damage D_{env} in four driving environments—urban, rural, highway, and circuit—was calculated. A target damage function was established by applying weighting factors based on Hyundai Motor's high-performance vehicle powertrain durability mode driving ratios:

$$D_{target} = w_u D_u + w_r D_r + w_h D_h + w_c D_c$$

Referencing the cyclic torque-differential test structure from U.S. Patent US7316156B2, two representative test modes were designed: ① **High-Load/Low-Differential-Speed** (near lock-up condition, differential speed ratio $\leq 10\%$) and ② **Low-Load/High-Differential-Speed** (repeated unlocking-partial locking, high-slip condition).

Urban and rural driving showed low torque and RPM, highway driving exhibited extended continuous load with relatively low contact stress, while circuit driving demonstrated the highest pitting damage per unit time due to high RPM, rapid slip rate changes, and repeated high-power sections. Notably, over-differential conditions were locally observed during circuit driving.

This study demonstrates that Morrison-equation-based fatigue analysis of real vehicle circuit data enables accurate quantification of m-LSD cam-ring pitting damage severity across driving environments. The resulting target damage function and revised bench test modes provide a practical foundation for reliability-driven durability testing of m-LSD systems in future high-performance EVs.

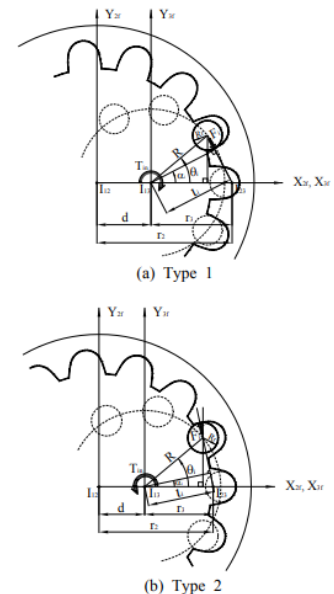


Fig.1 Contact Force at the i-th Cam Angle raph