

Development and Performance Evaluation of an MR Fluid Active Damper Tube

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Increasing demands for both ride comfort and vehicle handling stability have accelerated the development of suspension systems capable of real-time damping control. Conventional hydraulic variable dampers generate damping force primarily as a function of piston velocity, limiting their effectiveness in low-speed and micro-vibration regions frequently encountered during everyday driving. To address these limitations, this study developed a Magnetorheological Fluid Active Damper Tube (MRDT), a semi-active rotary damper capable of continuously varying damping force through magnetic-field control of magnetorheological (MR) fluid.

The proposed MRDT converts linear suspension motion into rotational motion through a ball-screw mechanism. A cylindrical rotor immersed in MR fluid generates controllable shear stress when subjected to a magnetic field. By regulating the coil current, the magnetic field strength and the resulting yield stress of the MR fluid can be adjusted in real time, enabling rapid and continuous damping-force control independent of piston velocity.

To identify the most suitable damper architecture, valve-type, disk-type, and tube-type MR damper configurations were analytically compared using force-generation coefficient and dynamic range as evaluation metrics. Results showed that the tube-type configuration provided the highest force-generation efficiency and the largest controllable damping range, making it the most appropriate structure for high-performance automotive applications.

A magnetic circuit optimization methodology was then established to reduce weight while maintaining torque performance. The study introduced magnetic circuit efficiency as a key design parameter and investigated the relationship among magnetic flux density, coil turns, and magnetic circuit geometry. Electromagnetic analysis demonstrated that excessive magnetic saturation could be suppressed while preserving the required torque output. The optimized design achieved a 23% reduction in mass, a 68% reduction in coil turns, and approximately 36% faster response compared with the conventional design.

Finite-element electromagnetic simulations confirmed improved magnetic flux distribution, reduced saturation, enhanced maximum torque capability, and better power efficiency. Prototype testing showed good agreement with simulation results for both torque characteristics and transient response behavior, validating the analytical model. Minor discrepancies were attributed to the hysteresis and viscosity characteristics of the MR fluid and mechanical friction effects.

Furthermore, the optimized MRDT was installed in a test vehicle and evaluated under highway driving conditions. Measured piston velocity and damping-force data confirmed stable operation throughout the normal driving range and demonstrated sufficient responsiveness to transient high-input events such as road joints and surface irregularities. These results indicate that the developed MRDT can contribute to both vehicle stability and ride comfort while maintaining effective damping performance under diverse operating conditions.

In conclusion, the proposed magnetic circuit optimization method significantly improved the torque density, efficiency, and responsiveness of the MRDT. The combination of analytical validation, prototype testing, and vehicle-level evaluation confirms the practical feasibility and future potential of MRDT technology for automotive semi-active suspension systems.