Post-print of "Study on the Impact Resistance Characteristics of a Novel Anti-Impact Hydraulic Support"

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Abstract

To address the problems that existing impact-resistant support structures for hydraulic supports cannot achieve active yielding and pressure relief, this study, building on previous research on a composite impact-resistant device, conducts an in-depth investigation into the impact-resistant characteristics of a novel anti-impact hydraulic support based on the composite impact-resistant device. An impact dynamics model of the novel anti-impact hydraulic support is constructed, the optimal installation position of the composite impact-resistant device is explored, and the influence of the composite impact-resistant device on the impact-resistant performance of the hydraulic support under different loads and different current conditions is examined. On the basis of the theoretical research, a prototype product was developed and experimental verification was carried out. The results show that the composite impact-resistant device can effectively reduce the peak impact force. When currents of 0, 1, and 2 A are applied to the composite impact-resistant device, under an impact load of 1.1 times the working load, the peak impact force is reduced by 2.23%, 1.68%, and 1.11%, respectively; under an impact load of 1.25 times the working load, the peak impact force is reduced by 4.41%, 3.22%, and 2.01%, respectively; and under an impact load of 1.4 times the working load, the peak impact force is reduced by 7.62%, 5.81%, and 3.23%, respectively. In combination with the impact dynamics model, a semi-active control strategy based on improved bang-bang control and fuzzy PID (proportional-integral-derivative) control is investigated, and a simulation model is established. The results indicate that the composite impact-resistant device can realize active yielding and active pressure relief, and can increase the energy absorption of the impact-resistant device while reducing the peak impact force acting on the hydraulic support columns.

Full Text

Research on Anti-Impact Characteristics of a New Anti-Impact Hydraulic Support

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Abstract

Existing anti-impact support structures for hydraulic supports cannot achieve active displacement and pressure release. Building upon previous research on composite anti-impact devices, this paper conducts an in-depth study on the anti-impact characteristics of a new anti-impact hydraulic support based on a composite anti-impact device. An impact dynamics model for the new anti-impact hydraulic support is constructed to investigate the optimal installation position of the composite anti-impact device and to examine the influence of different loads and current conditions on the anti-impact characteristics of the hydraulic support. Based on theoretical research, a prototype was fabricated and experimentally validated. The results demonstrate that the composite anti-impact device can effectively reduce impact peak forces. Under impact loads of 1.25 times the working load, the peak impact forces are reduced by 2.23%, 1.68%, and 1.11% when the composite anti-impact device is energized with 0 A, 1 A, and 2 A current, respectively. Under 1.4 times the working load, the reductions are 4.41%, 3.22%, and 2.01%, respectively. Under 1.55 times the working load, the reductions are 7.62%, 5.81%, and 3.23%, respectively. Combined with the impact dynamics model, semi-active control strategies based on improved Bang-Bang control and fuzzy PID control are investigated, and simulation models are established. The findings indicate that the composite anti-impact device can achieve active displacement and active pressure release, enhance the energy absorption capacity of the anti-impact device, and reduce the peak impact force on the support columns.

Keywords: anti-impact hydraulic support; dynamic model; anti-impact characteristics; semi-active control; experimental verification

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1. Introduction

With the development of the national economy and the increasing depletion of shallow coal resources, coal mining depth in China continues to increase. When coal seam mining reaches a certain depth, rock burst disasters caused by coal-rock structure instability often occur, posing significant threats to national property and people’ s lives. Hydraulic support technology in China developed rapidly in the 1980s, but for mines with frequent rock bursts, the primary methods for improving support strength and anti-impact capability involve advanced support and the addition of energy-absorbing components to hydraulic supports.

Existing anti-impact support structures are predominantly passive, unable to actively adjust support force or achieve active displacement and pressure release, limiting their effectiveness against rock bursts. Numerous scholars have investigated various energy-absorbing components, including corrugated laminated energy-absorbing elements on hydraulic support canopy beams, thin-walled circular tubes, ribbed-plate circular tubes, hybrid corrugated tubes, and magnetorheological (MR) damping technology. While MR dampers have been successfully applied in automotive, aerospace, and building seismic control fields, their application in hydraulic supports remains limited.

To address these limitations, the research team previously proposed applying MR buffering technology to hydraulic supports, demonstrating that MR buffer-equipped hydraulic supports can effectively reduce peak forces and exhibit superior anti-impact performance. Building upon this foundation, this study establishes an impact dynamics model for a hydraulic support based on a composite anti-impact device, investigates the optimal installation position of the composite device, and examines its performance under various loads and current conditions, with experimental validation of the theoretical findings.

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2. Design of Anti-Impact Hydraulic Support Based on Composite Anti-Impact Device

The anti-impact hydraulic support based on the composite anti-impact device is illustrated in [Figure 1: see original paper]. This support is a two-leg design with a single-leg rated working resistance of 2400 kN, yielding a total support rated working resistance of 4800 kN.

The structural diagram of the composite anti-impact device is shown in [Figure 2: see original paper]. The device consists of an energy-absorbing component and an MR buffer. Key parameters for these components are listed in .

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3. Mechanical Modeling of Composite Anti-Impact Device

The mechanical model of the composite anti-impact device comprises four parts: the MR buffer mechanical model, the MR buffer electromagnetic model, the energy-absorbing component mechanical model, and the anti-impact hydraulic support mechanical model under impact loading.

3.1 MR Buffer Mechanical Modeling During impact, the MR buffer operates in shear-valve mode. The damping force includes viscous damping force, inertial resistance, and friction force. The constitutive equation can be expressed using the Bingham model, where the total damping force F_{MR} comprises viscous damping force F_η, inertial resistance F_ρ, and throttling resistance F_τ:

$$F_{\mathrm{MR}} = F_\eta + F_\rho + F_\tau$$

where A_p is the piston effective working area, ρ is the MR fluid density, A_g is the piston working area, w is the compensation coefficient, and h is the equivalent plate thickness.

3.2 MR Buffer Electromagnetic Model The MR fluid employed is type A186. The relationship between magnetic flux density B and magnetic field intensity H, as well as between yield stress τ_y and magnetic flux density B, is shown in [Figure 3: see original paper]. The yield stress τ_y exhibits positive correlation with B.

COMSOL software was used to simulate the MR buffer [33]. Electromagnetic simulation analysis under different currents reveals the magnetic flux density distribution and magnetic induction lines within the damping channel, as shown in [Figure 4: see original paper]. The results demonstrate that the magnetic field is uniformly distributed around the damping channel, enabling generation of substantial damping force, while regions distant from the damping channel (such as the MR fluid and piston rod) experience negligible magnetic field, validating the rationality of the piston dimension design.

Statistical analysis of magnetic flux density under various currents yields the relationship between excitation current I, magnetic flux density B, and yield stress τ_y, presented in . Data fitting produces the mathematical relationship shown in [Figure 5: see original paper]:

$$\tau_y = 14.66I^2 + 2.332I + 0.974$$

3.3 Energy-Absorbing Component Mechanical Model Based on the research team’ s previously developed energy-absorbing component, crush tests were conducted on a 5000 kN electronic universal testing machine. The relationship between the component’ s crush reaction force and deformation is shown in [Figure 6: see original paper]. Research data indicate that the component undergoes elastic deformation before reaching maximum reaction force, followed by plastic deformation. The stage where reaction force decreases then increases represents the densification phase.

The test values of reaction force and equivalent stiffness were segmented and fitted polynomially for deformation ranges of 0–2.5 mm, 2.5–20 mm, and 20–100 mm, yielding the relationship between reaction force $F_{\text{支}}$ and deformation x:

$$F_{支} = \begin{cases} 5 \times 10^5 x^3 - 1.051 \times 10^5 x^2 + 597.2x + 158.3, & 0 \le x < 2.5 \\ -2.332 \times 10^4 x^2 + 974.5x + 22, & 2.5 \le x < 20 \\ 1.037 \times 10^5 x^2 - 1.758 \times 10^3 x + 319.2, & 20 \le x < 100 \end{cases}$$

3.4 Anti-Impact Hydraulic Support Mechanical Model Under Impact Loading The composite anti-impact device was positioned both below and above the support legs to construct an impact dynamics model with the device and legs as core components and rock burst equivalent impact force as input. According to Newton' s second law, the differential equation for the mechanical model with the device below the legs is:

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - F_{\mathrm{MR}} = F_{\mathrm{impact}}$$

With the device above the legs, the equation becomes:

$$m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2x_2 - F_{\mathrm{MR}} = F_{\mathrm{impact}}$$

These models are illustrated in [Figure 7: see original paper].

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4. Study on Anti-Impact Characteristics

4.1 Influence of Composite Anti-Impact Device Installation Position Considering the effect of control current on anti-impact characteristics, the rated working load was applied as system input with control currents of 0 A, 1 A, and 2 A. Displacement curves of the support legs and composite anti-impact device under different installation positions and currents are shown in [Figure 8: see original paper].

Results demonstrate that the composite anti-impact device provides anti-impact protection whether installed above or below the legs. However, installation above the legs yields superior pressure-releasing characteristics for the anti-impact hydraulic support. Under identical current, both leg displacement and device displacement are greater when installed below the legs compared to above. Under identical installation position, increasing current strengthens the device' s resistance, reducing both leg and device displacement while shortening the overall impact duration.

Post-impact replacement of the composite anti-impact device is necessary. Installation below the legs may cause jamming due to energy-absorbing component deformation, increasing replacement difficulty. Therefore, installation above the legs is more favorable.

4.2 Influence of Composite Anti-Impact Device on Hydraulic Support Anti-Impact Characteristics Impact process simulations were conducted under normal working conditions (rated working load of 2000 kN) with peak impact loads of 1.25 and 1.4 times the rated working load. [Figure 9: see original paper] presents the force on support legs under different impact loads and currents with the composite anti-impact device installed.

Comparison of leg forces with and without the composite anti-impact device under various impact loads and currents reveals that during initial impact stages, the impact force does not cause leg displacement while the composite device exhibits greater displacement than the legs, confirming its buffering and energy-absorbing function.

Under 1.25 times working load impact, compared with no device, peak impact forces are reduced by 2.23%, 1.68%, and 1.11% with 0 A, 1 A, and 2 A current, respectively, with peak delays of 4.06 ms, 3.38 ms, and 2.34 ms. Under 1.4 times working load, reductions are 4.41%, 3.22%, and 2.01% with delays of 4.88 ms, 3.99 ms, and 2.66 ms. Under 1.55 times working load, reductions are 7.62%, 5.81%, and 3.23% with delays of 6.97 ms, 6.42 ms, and 2.86 ms.

These results indicate that under identical impact load, increasing current increases the device' s resistance, reducing leg displacement and impact peak force. Under identical current, increasing impact load enhances the device' s anti-impact capacity accordingly.

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5. Semi-Active Control Strategy

To enhance the anti-impact capability of the device, semi-active control strategies were investigated using the dynamics model.

5.1 Improved Bang-Bang Control The Bang-Bang control algorithm operates by outputting maximum Coulomb force only when the total reaction force exceeds threshold F^* during increase, enabling the MR buffer to remain inactive during normal support. When total reaction force falls below F^* again, minimum Coulomb force is output for active displacement.

The improved Bang-Bang control introduces F_z in the region where $F \cdot k > 0$, in addition to threshold F^*, ensuring the MR buffer remains inactive during normal support while providing clear weakening during impact. The control expression is:

$$I = \begin{cases} I_{\text{max}}, & F_{\text{total}} > F^* \\ I_{\text{min}}, & F_{\text{total}} \leq F^* \end{cases}$$

Simulation results show the improved Bang-Bang control reduces peak reaction force by 7.8% compared to passive impact, with energy absorption approaching that of passive impact without significant reduction. The control algorithm induces crushing of the energy-absorbing component before peak arrival, enabling active displacement and preventing the legs from bearing greater peak pressure.

[Figure 13: see original paper] shows the current variation curve under improved Bang-Bang control, while [Figure 14: see original paper] compares the damping force curves under improved Bang-Bang control and passive impact, demonstrating greater energy absorption under active control.

5.2 Fuzzy PID Control The fuzzy PID control system consists of an adjustable PID controller and fuzzy control system. The fuzzy controller adaptively modifies PID parameters (K_p, K_i, K_d) based on error E between actual and desired reaction force and its change rate $\dot{E}$, enhancing control effectiveness and anti-interference capability.

The fuzzy rule tables for parameter tuning are established by fuzzifying inputs E (domain [-6,6]) and $\dot{E}$ (domain [-0.6,0.6]) with fuzzy subsets {NB, NM, NS, ZE, PS, PM, PB}. The resulting control rule tables are shown in , , and .

[Figure 16: see original paper] presents the current variation curve under fuzzy PID control, while [Figure 17: see original paper] compares the damping force under fuzzy PID and improved Bang-Bang control. The fuzzy PID control demonstrates superior overall energy absorption, with its damping force slightly higher than improved Bang-Bang control during mid-simulation while performing similarly in early stages.

[Figure 18: see original paper] compares the reaction forces, showing identical peak values but better energy absorption for fuzzy PID control.

5.3 Composite Control Based on Improved Bang-Bang and Fuzzy PID A composite controller combining improved Bang-Bang and fuzzy PID control was designed to leverage both algorithms' advantages, enabling both active displacement and superior energy absorption. The composite control maintains the damping force of improved Bang-Bang before the switching point and fuzzy PID after switching, as shown in [Figure 19: see original paper].

[Figure 20: see original paper] shows the current variation curve under composite control, while [Figure 21: see original paper] compares the damping force curves. [Figure 22: see original paper] demonstrates that the composite control achieves the same peak reaction force reduction as improved Bang-Bang while providing better overall energy absorption.

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6. Experimental Research

Based on previous research, a test prototype was fabricated by simplifying the hydraulic support legs and composite anti-impact device.

6.1 Test System The test system schematic is shown in [Figure 23: see original paper]. The system primarily comprises the test bench mechanical structure, displacement sensors (range 100 mm, accuracy $±$0.1%, resolution 0.01 mm), pressure sensors (range 0–25 MPa, accuracy 0.5% F.S.), data acquisition system, current controller, and power supply.

6.2 Verification of Different Installation Positions The MR buffer was installed both above and below the legs with impact block mass of 200 kg and impact distance of 200 mm. The current controller applied currents of 0 A, 1 A, and 2 A, with the data acquisition system recording dynamic data during impact.

[Figure 24: see original paper] compares simulated and experimental displacement curves of the MR buffer at different installation positions, showing consistent trends. Under identical impact conditions and current, displacement is greater when installed below the legs than above, with both displacement and impact duration decreasing as current increases.

[Figure 25: see original paper] presents the pressure curves on legs under different installation positions at 0 A current, showing greater pressure when the buffer is below the legs. Leg pressure decreases with increasing current.

[Figure 26: see original paper] shows the test displacement curves of the MR buffer at different installation positions, confirming that installation below the legs absorbs more energy due to the legs' own weight, leaving less capacity for impact energy absorption. This indirectly validates that installation above the legs is optimal.

6.3 Anti-Impact Characteristics Test of Equivalent Column With impact block mass of 200 kg and impact distance of 800 mm, impact tests were conducted on columns without and with the composite anti-impact device. [Figure 27: see original paper] shows the crushed morphology of the composite device and anti-impact column under different currents, revealing optimal anti-impact capacity and energy absorption at 0 A, with performance decreasing as current increases.

[Figure 28: see original paper] compares simulation values under 1.4 times working load impact with experimental values at 800 mm impact distance, demonstrating that installing the MR buffer effectively reduces and delays the peak force on the column. Changing current can adjust the peak impact force, with experimental characteristics matching simulation trends.

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7. Conclusions

This study investigated the anti-impact characteristics of a hydraulic support equipped with a composite anti-impact device, establishing an impact dynamics model and proposing semi-active control strategies validated through experiments.

1. An impact dynamics model was established for the anti-impact hydraulic support based on the composite anti-impact device. The optimal installation position was studied, with experimental analysis confirming that installation above the legs absorbs more rock burst energy and effectively reduces peak force, validating its superiority.
2. The anti-impact characteristics of the new hydraulic support were studied through simulation and experimentally validated. Results show the composite anti-impact device effectively reduces impact peak forces: under 1.25 times working load, peak forces are reduced by 2.23%, 1.68%, and 1.11% at 0 A, 1 A, and 2 A current, respectively; under 1.4 times working load, reductions are 4.41%, 3.22%, and 2.01%; under 1.55 times working load, reductions are 7.62%, 5.81%, and 3.23%.
3. A semi-active control strategy for the composite anti-impact device under impact loading was proposed, combining improved Bang-Bang and fuzzy PID control. The composite anti-impact device can achieve active displacement and active pressure release, enhance energy absorption capacity, and reduce peak impact forces on support columns.

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