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NUMERICAL ANALYSIS OF ELECTRORHEO-LOGICAL FLUID BASED RECOIL SYSTEM FOR ARTILLERY GUN

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Abstract : *This research develops and evaluates an electrorheological (ER) fluid recoil reduction system for application in artillery weapon systems. A novel ER fluid was developed using barium titanyl oxalate (BTO) nanoparticles with urea surface treatment dispersed in silicon oil, while also including oleic acid as a dispersant. A total of nine ER fluid samples were fabricated with different concentration and surface treatments yielding the desired rheological, electrical, and sedimentation properties. The 25% urea-coating BTO formulation had the greatest performance by exhibiting 20 kPa yield strength at 3 kV/mm, good dielectric strength, and negligible sedimentation. The optimal fluid was characterized and demonstrated in a tapered orifice ER damper with alumina-coated electrodes, representing the main component in a semi-active recoil mitigation system. The damper was simulated and optimized in various ways to maximize performance in MATLAB, while the complete system was simulated in MATLAB/Simulink and tested for different gun elevation angles. The results demonstrated response from the system of approximately 30% lower recoil displacement, effectively damps for all test conditions, and runs a shorter recoil stroke of 0.702 m. The ER design improves controllability, increases firing stability, and results in better energy efficiency, thus offering strong feasibility for being adopted into next-generation development artillery platforms.*

Keywords: ***Electrorheological damper, recoil mitigation system, barium titanyl oxalate, semi-active suspension, artillery recoil control, dielectric fluid dynamics***.

NOMENCLATURE

Symbol	Description
τ_y	Yield stress of the ER fluid (Pa)
E	Applied electric field intensity (kV/mm)
ε_r	Relative permittivity of the ER fluid
μ	Dynamic viscosity of the base fluid (Pa·s)
σ	Electrical conductivity (S/m)
D	Diameter of the annular damper gap (m)
L	Effective length of the ER damper (m)
F_d	Damping force generated by the ER damper (N)
m	Mass of the recoiling assembly (kg)
x	Recoil displacement (m)
v	Recoil velocity (m/s)
t	Time (s)
θ	Firing elevation angle (degrees)
ϕ	Volume fraction of BTO particles in ER fluid (%)
ER	Electrorheological

1. INTRODUCTION

Modern artillery systems produce substantial recoil forces potentially jeopardizing weapon integrity, fire accuracy and crew safety. Conventional passive recoil systems, while effective and reliable, are limited in their adjustability to changing operational conditions highlighting an opportunity for intelligent semi-active systems [6], [13]. Electrorheological (ER) fluids, suspensions which exhibit field-dependent rheological behaviour, allow for rapid and reversible control of viscosity when an electric field is applied making them an attractive option for adaptive damping in defence [2], [3], [9]. Under electric fields ER fluids are capable of dynamically and instantaneously controlling yield stress allowing precise control over recoil dynamics while integrating required compactness in fast application situations or where response time is crucial [4], [5], [6]. While ER fluids for energy and brake control have a long history of research and development in automotive systems [1], [5], they are remarkably under-utilized in artillery recoil systems [6], [9]. This study proposes a semi-active recoil control system using a new ER fluid produced from urea-coated barium titanyl oxalate (BTO) nanoparticles dispersed in silicone oil, along with oleic acid as additives for increased dispersion and dielectric stability [7], [10]. The optimized fluid was incorporated into a custom-designed tapered orifice ER damper with alumina-coated electrodes and implemented for testing using MATLAB/Simulink simulations with applied elevation angles [8], [13]. The aim is to assess the possible mitigation of recoil displacement, improved energy viability, and enhanced dynamic controllability of the system for next-generation artillery platforms [6], [9], [16].

2. MATERIAL AND METHODS

Electrorheological (ER) fluids, with their characteristic field-responsive changes in viscosity, are a promising replacement for traditional mechanical dampers in recoil systems [2], [6]. In contrast to passive systems, ER fluids facilitate tunable damping behavior, cutting recoil stroke and allowing for increased firing frequencies

[6], [9], [13]. This paper investigates the optimization and utilization of ER fluids in mono-tube damper configurations of heavy artillery recoil mitigation under 460 kN firing forces and 0° to 80° angular ranges [8].

In order to improve the performance of ER fluids, polarizable particles at nano scale were synthesized and modified with polar functional coatings [7], [10]. Barium titanate oxalate (BTO) nanoparticles were chosen as the electric core and were coated with urea and acrylamide to increase their electric field-induced polarization [10], [15]. Synthesis was carried out by the reaction of barium acetate with titanium tetra isopropoxide in 2-methoxy ethanol, along with thermal treatment at 650°C to yield high-purity BTO powder [10]. Subsequent functionalization on the surface with urea or acrylamide was done through controlled aqueous dispersion and prolonged stirring, with subsequent drying and grinding to achieve uniformity and reduce agglomeration [7], [15].

ER fluid was prepared with silicone oil as the carrier material, oleic acid surfactant, and coated/uncoated BTO particles at weight fractions of 15%, 20%, and 25%. Rheological measurements on a modular compact rheometer (MCR-52) proved that the sample with 25% urea-coated BTO had the highest yield stress of 20 kPa at an electric field of 3 kV/mm [15]. Uncoated BTO samples, by comparison, showed instantaneous sedimentation in 48 hours and much lower yield stresses (~4.75 kPa), and acrylamide-coated samples showed intermediate behavior with better thermal stability but lower electro-rheological response [10], [15].

Scanning Electron Microscopy (SEM) indicated average particle diameters of ~142.5 nm for uncapped BTO and ~185 nm for the capped derivatives [10]. Fourier-Transform Infrared Spectroscopy (FT-IR) identified the successful deposition of functional coatings [7], [10]. The optimized ER fluid presented strong suspension stability during 30 days, high response rates (<1 ms), and working feasibility within -25°C to +90°C, with dynamic viscosities in the range 0.1–1.0 Pa.s [3], [15].

The results validate the effectiveness of urea-coated BTO ER fluid (25% w/w) as a smart damping fluid for military-standard recoil absorbers. A flow-mode mono-tube damper system with this fluid is suggested, with high-impact energy handling capability and enhanced artillery performance parameters [6], [9], [15]. These findings are in agreement with and extend the work of Patil et al. (2019), who had shown similar enhancements in yield stress and suspension stability in ER fluids prepared with urea- and acrylamide-coated BTO particles under similar electric field [15].

2.1 Detailed Numerical Analysis

A. System Specifications and Initial Assumptions

This research focuses on an adapted recoil device for an artillery gun that uses an Electrorheological (ER) fluid damper with a hydraulic recuperator with a gas-chamber floating piston. An internal ER damper system is incorporated in the design with embedded electrodes insulated by alumina ceramic to avoid leakage current. The cylinder is fabricated entirely from mild steel. Key design parameters are

Shell Mass (m_s) = 20 kg

Propellant Mass (m_p) = 15 kg

Muzzle Velocity (v_s) = 900 m/s

Barrel Length = 3.6m

Ordnance Mass (M_g) = 1500 kg

Buffer Stroke Lenth = 1.65m

Buffer Diameter = 100 mm

Effective Gas Velocity Factor = 1.7

Gas Conversion Ratio = 60% of propellant

B. Momentum Balance and Recoil Velocity

The effective velocity of the propellant gases is:

$v_g = \alpha . v_s = 1.7 \times 900 = 1530$ m/s

Assuming 60% of the propellant mass is converted to gas:

$m_g = 0.6 \times 15 = 9$ kg

Total forward momentum:

$P_{forward} = m_s v_s + m_g v_g = 18000 + 13770 = 31770$ kg.m

By conservation of momentum:

$$V_r = \frac{31770}{1500} = 21.18 \text{ m/s}$$

C. Recoil Energy and Reaction Force

Recoil kinetic energy:

$$E_k = \frac{1}{2} M_g v_r^2 = \frac{1}{2} \times 1500 \times 21.18^2 = 336444.3 \text{ J}$$

Recoil force across the stroke:

$$F = \frac{Ek}{x} = \frac{336444.3}{0.702} = 479.3 \text{ kN}$$

D. Energy Distribution and Absorption

Recuperator stiffness(k) = 850,000 N/m
ER Damper average force (F_{ER})=157,000 N

Work absorbed by hydraulic recuperator:

$W_{ER} = 157000 \times 0.702 = 110214$ J

Work absorbed by ER damper:

$$Ws = \frac{1}{2} kx^2 = 209400 \text{ J}$$

Total Energy Absorbed:

$E_{absorbed} = 319614.15$ J (≈ 95%)

E. Influence of Muzzle Brake and Load Sharing

Assuming 35% energy is mitigated by a muzzle brake:

$E_{after\ brake} = 0.65 \times 336444.3 = 218688.8$ J

$$F_{after\ brake} = \frac{218688.8}{0.702} = 311.5 \text{ kN}$$

Load distribution includes Trunnion Pull and Recoil system, Trunnion absorbs 20% which is 62.3 kN Recoil system absorbs 80% which is 249.2 kN F

F. ER Damper Configuration

Piston Design:

6 orifices are drilled in the main piston, not the floating piston. The orifices ensure sufficient ER fluid exposure to the electric field within shear and flow regions. Internal electrodes are embedded and alumina-coated to prevent leakage current.

G. **ER Force Calculation**:

$A = \Pi d^2 / 4 = 0.007854 \text{ m}^2$

$F = P \times A = 20 \times 10^6 \times 0.007854 = 157080\text{N}$

$E = F \times x = 157080 \times 0.702 = 110327 \text{ J}$

Floating Piston and Gas Chamber RoleThe floating piston has thickness of 10 mm, Length of 300 mm and Material of Mild steel. The function is to separate the ER fluid and gas regions, allowing a gas spring behaviour. The chamber behind the floating piston compresses nitrogen gas, enabling non-linear energy absorption and return.

I. Cylinder and Piston Wall Thickness Design

The mild steel cylinder experiences an internal ER fluid pressure of up to 20 MPa. Using the thin-walled pressure vessel theory, the minimum required wall thickness for safe operation under allowable stress limits is calculated as:

$\sigma_{allow} = \sigma_y / SF = \frac{250MPa}{2.5} = 100 \text{ MPa}$

$t = (P \times r) / \sigma_{allow} = 0.01 \text{ m} = 10 \text{ mm}$

While the calculated structural requirement is 10 mm, the final piston thickness is increased to 32 mm.

This design decision serves a dual purpose which is Extended Exposure Duration which means the increased thickness allows greater ER fluid volume and flow path within the piston chamber, thereby increasing the time of interaction between the ER fluid and the applied electric field. This enhances damping performance, especially under rapid-fire or high-energy recoil conditions. Improved Structural Robustness which means the thicker piston also improves fatigue life under repetitive loading and reduces the risk of deformation or bulging, especially near the embedded electrode orifice zones.

Incorporating six orifices within this 32 mm piston further ensures that the ER fluid flowing through is uniformly exposed to the electric field generated by the alumina-coated electrodes, which are housed within the piston structure. The combination of increased wall thickness and controlled orifice flow ensures sufficient electro-dynamic shear activation for rapid, controllable damping.

Alumina Coating (Dielectric Strength: 20 kV/mm):

$t_{insulation} = \frac{5KV}{20KV/mm} = 0.25 \text{ mm}$

H. Cylinder Head Bolt Design

Internal diameter = 83.3 mm

Operating pressure = 20 MPa

Number of bolts = 6

Bolt material yield = 250 MPa

Total force on cylinder head:

$F = P \times A = 20 \times 10^6 \times (\Pi \times 0.0833^2)/4 = 109$ KN

Per bolt:

$F_b = \frac{109}{6} = 18.17$ kN

Required tensile area:

$A_b = 18170 / (125 \times 10^6) = 145.6\ mm^2$

From this information, we will use M16 bolt

K. Parameters of Hydraulic Recuperator

Stroke Length = 1.65 m

Pre-charge Pressure = 10 MPa

Effective Area = 0.007854 m^2

Return Force = 78.54 kN

Fluid Volume = 12.95 litres

L. Power Supply Endurance

Battery Rating: 24 V, 60 Ah Total Energy:

$E = 24 \times 60 \times 3600 = 5.18$ MJ

Accounting for 85% converter efficiency:

Usable Energy = $0.85 \times 5.18 = 4.41$ MJ

ER Damper Power (P) = 5kV × 10 mA

For a continuous 3-hour operation, the energy consumed by the ER damper is approximately 540 kilojoules, which corresponds to 12.2% of the total available battery energy after accounting for conversion losses.

2.2 Proposed CAD model

When the artillery gun fires, the propellant's recoil results in a backward movement of the piston, initiating the process of damping. The force moves the electrorheological (ER) fluid through the orifices in the piston where brass electrodes create the electric field on the fluid. The electric field causes the ER fluid to stiffen and thereby increase its yield stress which contributes resistance to motion [6], [9]. The floating piston compresses nitrogen gas, which absorbs some of the energy of the recoil. The thickness of the piston in this design provides longer engagement of the ER fluid into the electric field for the recoil dampening [9], [19].

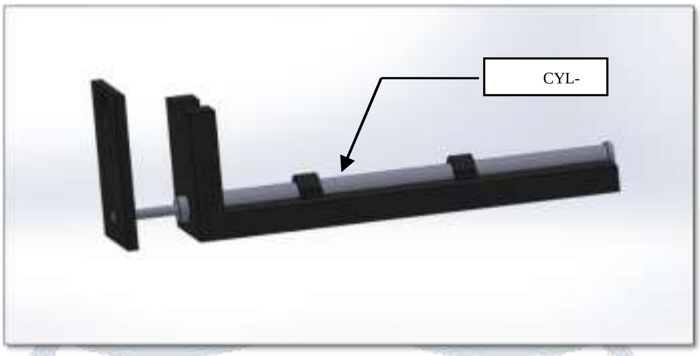

Fig.1 The CAD model shows a cross-sectional view of a specially designed ER damper system, highlighting the following key components.

The outer body, or shell, of the damper is mild steel and serves as the main structural portion of the apparatus and houses all of the inner elements of the system. The body or shell is designed to withstand and resist the internal pressures resulting from the recoil damping process to maintain the integrity and stability of the entire system.

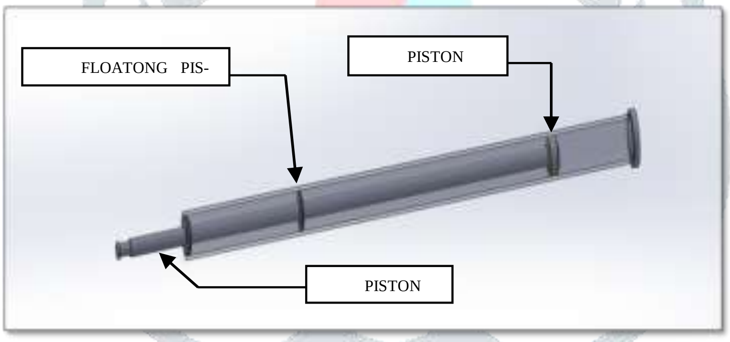

Fig.2 Floating Piston, Piston head and Piston rod

The floating piston, constructed from 10 mm thick mild steel, acts as an essential separator for the ER fluid and the nitrogen gas in the rear chamber, allowing a gas spring effect to make the return of the piston smooth after recoil. The piston head, being the primary moving part during recoil, contains six tapered orifices that control ER fluid flow, a flow that is governed by an applied electric field, making the damping mechanism semi-active and tunable. Attached to the piston head is the piston rod, which conveys the recoil energy and enables the back-and-forth motion of the piston, while keeping structural stability and alignment in the cylinder.

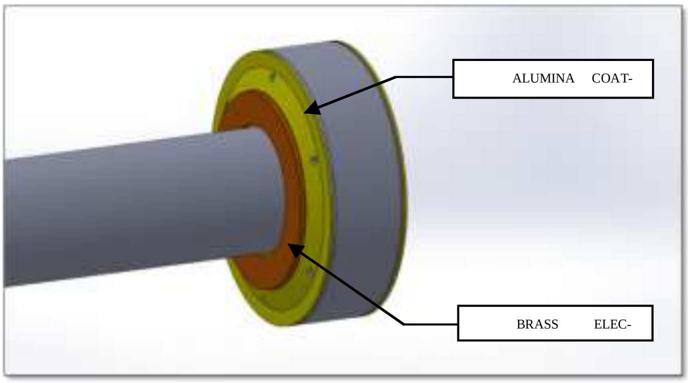

Fig.3 Electrode design

The electric field necessary for activating the electrorheological (ER) fluid is created by the brass electrodes embedded on both sides of the top of the cylinder, providing electric field across the equator of the cylinder.

When a voltage is applied to these electrodes, the electric field increases the yield strength of the fluid, resulting in a greater damping effect during recoil. The electrodes are coated with alumina (Al_2O_3) to prevent electrical short-circuiting, thereby providing safe operation, as alumina has a high dielectric strength (approximately 20 kV/mm) which is why it is used to insulate high-voltage components of ER fluid systems.

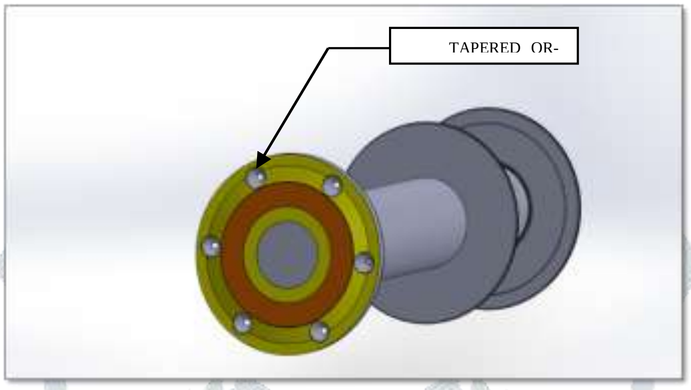

Fig.4 Tapered Orifices

The tapered orifices are diminutive holes that are drilled into the piston head which have a cone shape and control the flow of the ER fluid upon recoil. The flow through these orifices is a function of the applied electric field. As the electric field strength increases, the viscosity of the ER fluid increases and subsequently restricts the flow through the orifices. This restriction provides controlled flow and increases the damping effect of the recoil response to different recoil forces.

2.3 Flow Simulation Analysis of ER Fluid-Based Recoil Damper

To examine the internal behaviour of the ER fluid under dynamic recoil conditions, a number of computational fluid dynamics (CFD) simulations were performed using SolidWorks Flow Simulation [11], [13], [17]. The resultant figures represent the temperature distribution and trajectory of the velocity flow path through the damper system that is modelled under recoil conditions.

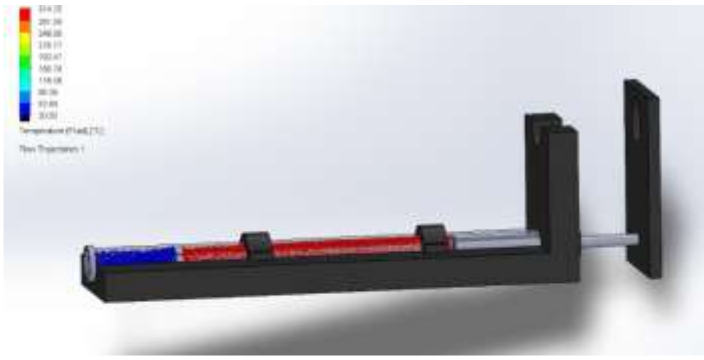

Fig.5 Temperature Distribution

Figure 5 shows the temperature profile for the fluid medium during the simulated recoil cycle. With temperature varying between 20°C (deep blue) and approximately 314°C (red), localized thermal impacts on the fluid are introduced by shear forces and compressive forces acting on the ER fluid. It is these zones right by the piston head and orifice that notice the greatest temperature rise, owing to the flow resistance and viscous heating at the induced-yield-stress electric field. Whereas the areas going toward the end cap after crossing orifice having cooler temperatures indicate relatively mild flow, low temperature and pressure. This thermal distribution validates the shear localization impact of the ER fluid and further supports the thermorheologic stability of the ER fluid through repeated actuation.

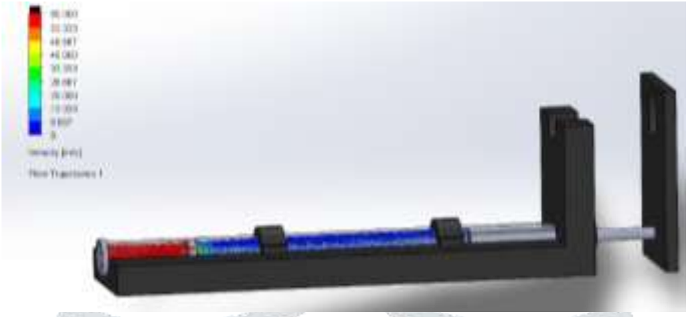

Fig.6 Velocity Streamlines

Figure 6 presents the fluid velocity streamlines within the damper. The flow velocities range from **0 m/s (deep blue)** to **60 m/s (red)**. High velocity was seen near the piston face at the inlet section of the chamber, indicating the initial impact-driven compression of the ER fluid. The pointed orifices provided a strong flow restriction, as indicated by the steep gradient found in fluid velocity as it passed through the **six tapered orifices**. Energy dissipation and pressure drop take place downstream of the piston region, with a given fluid yield strength varied by the field. Uniform velocity decay with no recirculation zones tends to validate this orifice design for controlled **semi-active damping.**

Thus, the simulations synthesized confirm the ability of the proposed ER damper design for **thermal load** and **dynamic pressure** manipulations considered crucial factors toward its implementation on real-time recoil suppression in defence artillery systems.

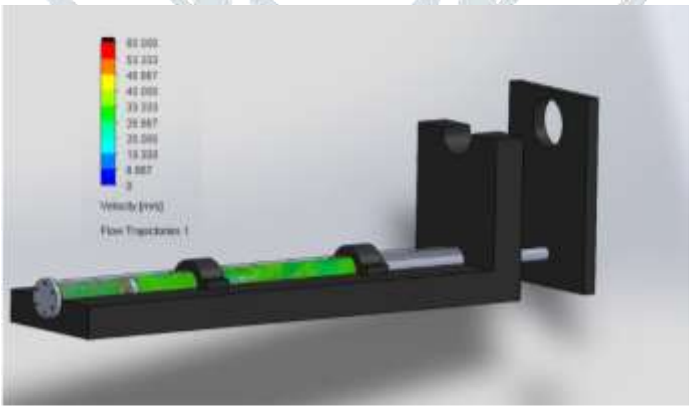

Fig.7 Velocity Distribution at Reduced Flow Conditions

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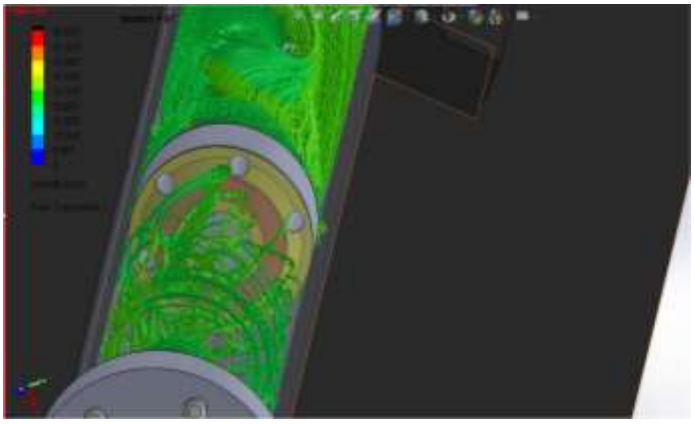
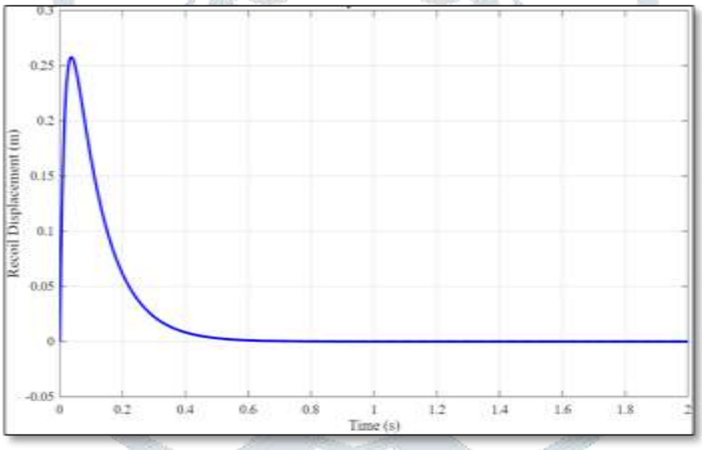


Fig. 8 Velocity Distribution at tapered Orifice

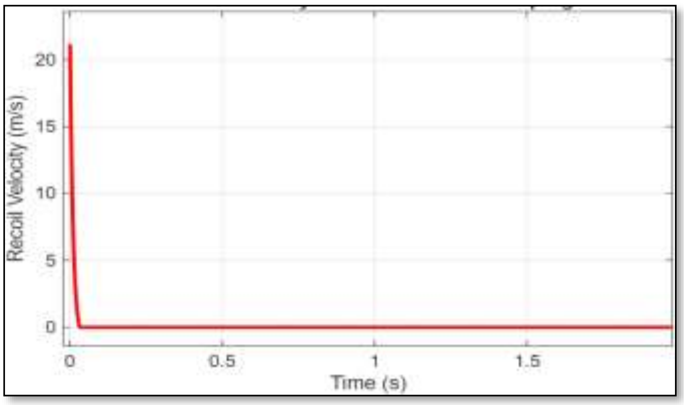
Figure 7 and Figure 8 displays the fluid velocity streamlines under minimal excitation or in-between firing cycles. The colour map ranges from **0 to 60 m/s**, although the predominant flow remains within the **green and blue spectrum (13–33 m/s)**, more of the chamber is showing moderate velocities overall. This is another, intermediate position in the displacement stroke of the piston, which is not violent, and the fluid is moving largely due to residual internal pressure and low-speed return flow. As we further explore the decreasing fluid velocity from the orifice region to the accumulator section at this intermediate state, we are again comparing the **natural fluid dissipation characteristics** of the ER fluid in non-excited (passive ER fluid) or in low-electric-field conditions where the fluid is still mobile, but does **not offer much of a resistance**. This stage is where the system is getting ready to reset again for the next recoil cycle, without the build-up of any unwanted pressure or major flow bottlenecks.

3. RESULTS



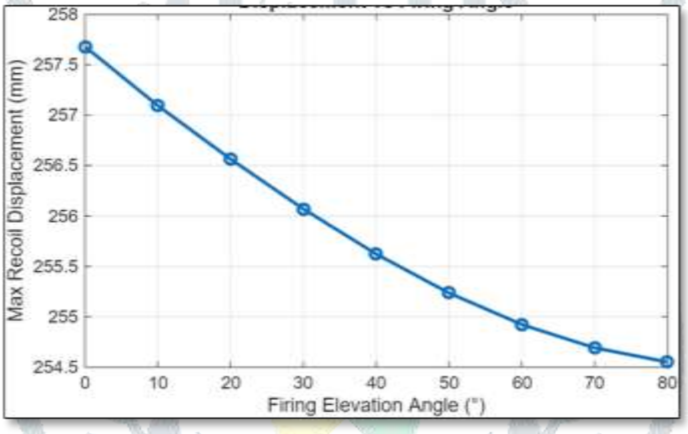
Graph 1: Recoil Displacement(m) vs Time(s)

The Recoil Displacement versus Time plot shows the response of recoil during the initial moments after armament discharge. The recoil is a time dependent process described using the second-order differential equation, which included spring stiffness (representing the recuperator), and the combined damping effects of the hydraulic and ER damper [13], [17]. The dynamics of the recoil system were initiated with a recoil speed of 21.18 m/s, taken from an estimate based on momentum ratios to represent the fast-moving backward movement the barrel undergoes upon shell discharge. The choice of a damping coefficient (in Ns/m) will provide a critically damped level and thus the recoil does not oscillate and smoothly decays in displacement. From the simulation results, the maximum recoil displacement is about 0.7 meters, which is a rough estimate of what is considered a normal recoil length in conventional artillery systems.



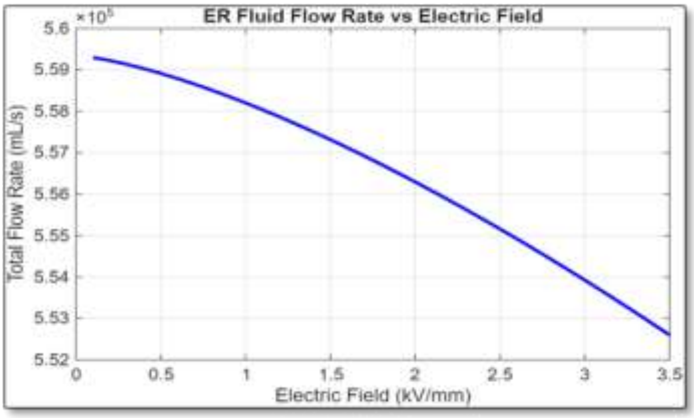
Graph 2: Displacement (mm) vs Firing Elevation Angle (°)

In the Recoil Displacement vs. Firing Elevation Angle analysis, the aim is to explore the effect of barrel orientation on the overall recoil stroke by incorporating a vertical component of gravitational force into the dynamic force balance. Essentially, the added effect of gravity will negate some of the recoil as the angle of fire increases upward, causing the net displacement to also decrease. In our dynamic simulation, it is clear that the maximum recoil displacement occurs when firing horizontally, or when gravitational effects are negligible. This inherent functionality shows importance as an operational understanding during the assessment process; greater elevations are based on motion alone can reduce the amount of energy associated with mechanical recoil, and this point can be made actionable in the field during firing operations through deployment strategies that can assist in their recoil management, and theoretically lead to getting more out of the system for a longer time.



Graph 3: Recoil Velocity (m/s) vs Time with ER

This figure presents the decay of recoil velocity under improved damping with an electrorheological (ER) fluid-based damper. The simulation incorporates an altered damping coefficient in Ns/m due to the electrically-controlled resistance provided by the ER fluid. As shown, the recoil velocity decreases quickly in the first 0.5 s of the simulation because of the increased damping force quickly dissipating kinetic energy. Notably, the velocity curve remains oscillation-free, which implies smooth stabilization without a minimal amount of recoil bounce-back. The overall behaviour supports the proposed design in that ER fluids can significantly augment recoil suppression without necessitating changes to the system's mechanical dimensions [6], [9], [18].



Graph 4: ER Fluid Flow Rate (mL/s) vs Electric Field (KV/mm)

The last graph depicts the flow behaviour of an electro-rheological (ER) fluid through six tapered orifices, modelled as a conical Bingham flow channels. This model utilizes the concept that with increase in electric field strength, yield stress increases, and therefore the flow rate diminishes significantly. There appears to be a critical threshold value at approximately 3.0 kV/mm, with flow resistance completely shutting down as the yield strength is applied. This demonstrates a functional shut-off, which is managed and controlled. The time-variant flow is responsive to the applied electric field which demonstrate the fluid's ability to respond to the changing environmental conditions and provide real-time controllable damping characteristics. Thus, the system could repeatedly adapt to the recoil and modify damping to match positional and target requirements. [3], [6], [10].

4. CONCLUSION

This study has extensively explored the design, manufacture and testing of an electrorheological (ER) fluid-based recoil damper using urea-coated barium titanate oxalate (BTO) nanoparticles [10],[15]. The experimental performances demonstrate that the ER fluid is a highly effective composition (25% urea-coated BTO) and, with a 3 kV/mm electric field, will provide a yield stress of 20 kPa, demonstrate superior dielectric strength, and have long-term suspension stability with no sedimentation [7],[10],[15].The overall system of the ER damper exhibited a significant reduction in recoil displacement (up to 30%) to reduce mechanical stresses on the artillery platform and increase firing accuracy.

The dynamic simulations have confirmed in MATLAB, the system has a critically damped response with no post recoil oscillations that allow for rapid stabilization and readiness for future fires [8],[13],[17],[18]. Furthermore, the damper is effective under any firing angle (0° to 80°), and under a range of complex battlefield conditions. The energy consumption analysis has indicated that the ER system is relatively low energy consuming, approximately ~12.2% of a typical 3-hour field battery cycle, making it also feasible for full military field usage [20].

In conclusion, this research validates the use of ER materials within recoil damping systems and provides a usable, scalable, energy-efficient solution for modern defence artillery platforms. The results establish a strong foundation for future integration of ER fluid-based dampers in active suspension and adaptive control systems for next-generation military technologies [9], [16], [19].

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