DESIGN STRATEGIES FOR HIGH-PERFORMANCE ELECTROMAGNETIC MASS DRIVERS

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DESIGN STRATEGIES FOR HIGH-PERFORMANCE ELECTROMAGNETIC MASS DRIVERS

by

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Submitted

in fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the



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NEW DELHI 110016, INDIA

JULY 2026

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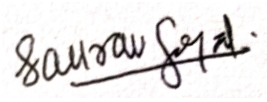
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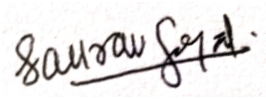
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Gaurav Goyal

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ABSTRACT

Electromagnetic mass drivers are solid-state propulsion systems that accelerate projectiles using Lorentz forces generated by high electrical currents flowing through parallel rails and a conductive armature. Their ability to deliver high-speed launches without moving mechanical components makes them attractive for particle accelerators, space propulsion, aerial vehicle launch and material testing applications. However, despite decades of development, electromagnetic mass drivers remain limited by fundamental uncertainties in the physics of sliding contact at extreme conditions, particularly at the armature-rail interface, where friction, heating, and transition phenomena are poorly understood and difficult to measure directly.

Chapter 1 outlines this central challenge: the physical processes that govern electromagnetic mass driver operation cannot be directly observed due to high currents, extreme accelerations, and transient timescales. Simulation becomes essential, but meaningful predictions require accurate input data, especially the coefficient of friction, which is unavailable for EMD conditions. To bridge this gap, Chapter 3 develops a validated, experiment-informed multiphysics simulation framework. Using data from a launch of a 0.12 kg projectile under a 1 MA current pulse (yielding a muzzle velocity of 2030 m/s), the simulation was calibrated to estimate the average coefficient of friction as $\mu_{\text{avg}} \approx 0.22$, with spatial variation from 0.5 to 0.1 along the barrel. Thermal analysis revealed that frictional heating dominated over Joule heating by more than a factor of four, identifying friction as the primary driver of thermal failure and armature transition.

This identification of friction as the dominant loss mechanism motivated a re-evaluation of armature design in Chapter 4. For achieving high muzzle velocities, it is desirable to minimize the required contact force; however, the lower limit for this force is not well defined in existing literature. The most commonly used guideline, the empirical gram-per-ampere rule, prescribes contact force based on peak current, but it lacks a theoretical foundation. To address this, a physics-based alternative was proposed using a welding-based failure hypothesis, which estimates the minimum contact force required to prevent interface melting. This formulation accounts for material properties and thermal-electrical coupling. Simulations of both monolithic and divided-contact armatures validated the approach, showing that armature failure is governed not solely by total current, but by localized current density and heating at discrete contact points. While divided-contact armatures improved current sharing and reduced peak heating, they also introduced new failure modes, including eddy-current-induced hotspots during current decay behavior.

Building on these insights, Chapter 5 addresses the design trade-off between contact force and mechanical compliance in C-armatures. Reducing armature length was shown to limit Lorentz-induced contact forces but also compromise structural flexibility. For example, a 60 mm C-armature was shortened to 29 mm to cap contact force at 100 kN, improving muzzle velocity but at the cost of compliance. To resolve this, a new hybrid armature was proposed, combining the conduction efficiency of a brush-type contact with the structural continuity of a monolithic armature. The hybrid design achieved a 1776 m/s muzzle velocity, reduced frictional losses from 14.5 kJ to 11.9 kJ, and satisfied all design constraints including contact force, stress, and current density.

Chapter 6 then shifts focus to the containment structure of the electromagnetic mass driver, where mechanical stiffness is critical for resisting magnetic forces during launch. A

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load path analysis revealed that conventional preload strategies relying on housing friction were unreliable and inconsistent. By redirecting bolt preload through the clamp plateelastic support interface, structural stiffness was increased from 70.6 MN/m to 231 MN/m. Further, the mechanical role of the housing was reintegrated into the clamp plate through geometric redesign, resulting in a filleted configuration that achieved friction-independent stiffness, reduced peak stress by 36%, and lowered the structural mass by 10%.

Taken together, this thesis advances the state-of-the-art in EMD research by addressing key uncertainties in contact physics, developing a validated simulation framework, proposing new theoretical models for failure prediction, and introducing practical design improvements for both the armature and structural containment.

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सार

विद्युत चुम्बकीय द्रव्यमान चालक ठोस अवस्था वाले प्रणोदन तंत्र हैं जो प्रक्षेप्य को उच्च विद्युत धाराओं द्वारा समानांतर छड़ों और एक चालक शस्त्रास्त्र में उत्पन्न लोरेन्ज बलों के माध्यम से त्वरित करते हैं। इनकी यांत्रिक गतिशील घटकों के बिना उच्च-गति प्रक्षेपण देने की क्षमता इन्हें कण त्वरकों, अंतरिक्ष प्रणोदन, वायुयान प्रक्षेपण और सामग्री परीक्षण अनुप्रयोगों के लिए आकर्षक बनाती है। हालाँकि दशकों के विकास के बावजूद, विद्युत चुम्बकीय द्रव्यमान चालक अभी भी अत्यधिक परिस्थितियों में फिसलन संपर्क की भौतिकी में मौलिक अनिश्चितताओं से सीमित हैं| विशेषकर शस्त्रास्त्र–छड़ इंटरफेस पर, जहाँ घर्षण, ऊष्मा, और संक्रमण संबंधी घटनाएँ अपर्याप्त रूप से समझी गई हैं और जिन्हें सीधे मापा जाना कठिन है।

अध्याय १ इस केंद्रीय चुनौती को रेखांकित करता है| विद्युत चुम्बकीय द्रव्यमान चालक के कार्य को नियंत्रित करने वाली भौतिक प्रक्रियाओं को सीधे नहीं देखा जा सकता क्योंकि इसमें उच्च धारा, अत्यधिक त्वरण और क्षणिक समयमान शामिल होते हैं। संगणक अनुकरण आवश्यक हो जाता है, परंतु सार्थक भविष्यवाणियाँ करने के लिए सटीक निविष्ट आँकड़े आवश्यक है, विशेषकर घर्षण गुणांक, जो विद्युत चुम्बकीय द्रव्यमान चालक स्थितियों के लिए अनुपलब्ध है। इस अंतर को पाटने के लिए, अध्याय ३ में एक मान्यताप्राप्त, प्रयोग-सूचित बहुभौतिकी संगणक अनुकरण ढाँचा विकसित किया गया है। ०.१२ कि.ग्रा. के प्रक्षेप्य को १ मे.एं. धारा के स्पंद के अंतर्गत प्रक्षेपित करने (२०३० मी./से. की नालमुख वेग प्राप्त) के आँकड़े का उपयोग कर संगणक अनुकरण का अंश-शोधन किया गया, जिससे औसत घर्षण गुणांक ०.२२ अनुमानित हुआ, जिसमें नाल के साथ ०.५ से ०.१ तक स्थानिक परिवर्तन था। तापीय विश्लेषण से पता चला कि घर्षणजनित ऊष्मा जूल ऊष्मा की तुलना में चार गुना अधिक थी, जिससे यह स्पष्ट हुआ कि घर्षण ही तापीय विफलता और शस्त्रास्त्र संक्रमण का मुख्य कारण है।

घर्षण को प्रमुख हानि तंत्र के रूप में पहचानने से अध्याय ४ में शस्त्रास्त्र बनावट का पुनर्मूल्यांकन प्रेरित हुआ। उच्च नालमुख वेग प्राप्त करने के लिए न्यूनतम संपर्क बल वांछनीय होता है; परंतु इस बल की न्यूनतम सीमा वर्तमान साहित्य में स्पष्ट नहीं है। सबसे सामान्यतः उपयोग में लाई जाने वाली "ग्राम-प्रति-ऐम्पियर" नियम, संपर्क बल को अधिकतम धारा के आधार पर निर्दिष्ट करती है, पर इसमें कोई सैद्धांतिक आधार नहीं है। इसे संबोधित करने हेतु, एक वेल्डिंग-आधारित विफलता परिकल्पना के माध्यम से एक भौतिकी-आधारित विकल्प प्रस्तावित किया गया, जो संपर्क के गलन को रोकने हेतु न्यूनतम संपर्क बल का अनुमान देता है। यह सूत्रीकरण सामग्री गुणों और ताप-विद्युत युग्मन को ध्यान में रखता है। एकल-संघटित और विभाजित-संपर्क शस्त्रास्त्रों के संगणक अनुकरण द्वारा इस पद्धति की पुष्टि की गई, जिससे ज्ञात हुआ कि शस्त्रास्त्र विफलता केवल कुल धारा से नहीं, बल्कि विशिष्ट संपर्क बिंदुओं पर स्थानीय धारा घनत्व और ऊष्मा द्वारा नियंत्रित होती है। विभाजित-संपर्क शस्त्रास्त्र ने जहाँ धारा वितरण में सुधार किया और शिखर ऊष्मा को कम किया, वहीं नए विफलता तंत्र को भी जन्म दिया, जैसे कि धारा क्षय के दौरान एड्डी करंट जनित स्थानिक तापन।

इन जानकारियों के आधार पर, अध्याय ५ में C-शस्त्रास्त्रों में संपर्क बल और यांत्रिक लचीलेपन के बीच के संरचनात्मक समझौते का विश्लेषण किया गया। शस्त्रास्त्र की लंबाई कम करने से लोरेन्ज-जनित संपर्क बल सीमित हुआ, परंतु संरचनात्मक लचीलापन भी घट गया। उदाहरण स्वरूप, ६० मि.मी. C-शस्त्रास्त्र को २९ मि.मी. तक छोटा किया गया ताकि संपर्क बल को १०० कि.न्यू. तक सीमित किया जा सके, जिससे नाल वेग में सुधार हुआ लेकिन लचीलापन घटा। इसे हल करने हेतु, एक नया वर्ण-संकर शस्त्रास्त्र प्रस्तावित किया गया, जिसमें कंघीनुमा-प्रकार संपर्क की चालकता दक्षता और एकल-संघटित C-शस्त्रास्त्र की संरचनात्मक अखंडता का संयोजन था। इस वर्ण-संकर संरचना ने १७७६ मी./से. का नाल वेग प्राप्त किया, घर्षणजनित हानियों को १४.५ कि.जूल से घटाकर ११.९ कि.जूल कर दिया, और सभी संरचनात्मक सीमाओं, संपर्क बल, तनाव, तथा धारा घनत्व, को संतुष्ट किया।

इसके बाद, अध्याय ६ में विद्युत चुम्बकीय द्रव्यमान चालक की परिरक्षण संरचना पर ध्यान केंद्रित किया गया, जहाँ प्रक्षेपण के दौरान चुंबकीय बलों का सामना करने हेतु यांत्रिक कठोरता आवश्यक

होती है। बल संचरण पथ विश्लेषण से ज्ञात हुआ कि हाउसिंग घर्षण पर आधारित पारंपरिक पूर्व-भार रणनीतियाँ अविश्वसनीय और असंगत थीं। बोल्ट पूर्व-भार को क्लैम्प प्लेट– एलास्टिक सपोर्ट संपर्क के माध्यम से पुनर्निर्देशित कर संरचनात्मक कठोरता को ७०.६ मे.न्यू./मी. से बढ़ाकर २३१ मे.न्यू./मी. कर दिया गया। इसके अतिरिक्त, हाउसिंग की यांत्रिक भूमिका को क्लैम्प प्लेट में ज्यामितीय पुनर्रचना के माध्यम से पुनः एकीकृत किया गया, जिसके परिणामस्वरूप एक राउंडेड कॉन्फ़िगरेशन प्राप्त हुआ जिसने घर्षण-स्वतंत्र कठोरता, शिखर तनाव में ३६ प्रतिशत की कमी, और संरचनात्मक द्रव्यमान में १० प्रतिशत की कमी प्राप्त की।

संपूर्ण रूप से, यह शोध विद्युत चुम्बकीय द्रव्यमान चालक पर अनुसंधान की वर्तमान स्थिति को आगे बढ़ाता है| फिसलन संपर्क की प्रमुख भौतिक अनिश्चितताओं को संबोधित कर, एक मान्यीकृत संगणक अनुकरण ढाँचा विकसित कर, विफलता भविष्यवाणी के लिए नए सैद्धांतिक मॉडल प्रस्तुत कर, और शस्त्रास्त्र व संरचनात्मक परिरक्षण दोनों के लिए व्यावहारिक संरचनात्मक सुधार प्रस्तावित कर।

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TECHNICAL DEFINITIONS & ABBREVIATIONS

A/R	Armature-Rail
Action out	The electrical action, defined as $\int I^2\,dt$, represents the cumulative thermal energy deposited into a conductor through Joule heating, normalized by resistance. Physically, actioning out signifies the threshold at which the accumulated thermal energy surpasses the material's specific heat capacity and latent heat of fusion.
Balloting	Transverse movement of armature inside the bore
Barrel/Bore	Length of EMD between breech and muzzle
Breech	EMD end from where the armature is inserted
CoF	Coefficient of friction
EMD	Electro-Magnetic Mass Driver
FEA	Finite Element Analysis
FEM	Finite Element Method
g/A rule	Gram-per-Ampere rule. It suggests that approximately 1 N of contact force per 100 A of peak current is sufficient to support reliable conduction. The **g/A** in SI units is equivalent to 0.01 N/A

Lorentz Constant $L = 2.45 \times 10^{-8}$ W·Ω·K^{-2} is the Lorentz constant in the Wiedemann-Franz law. This law dictates that the ratio of a metal's thermal conductivity to its electrical conductivity is directly proportional to its temperature.

Muzzle EMD end from where the armature exits

Transition A/R contact breaking

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