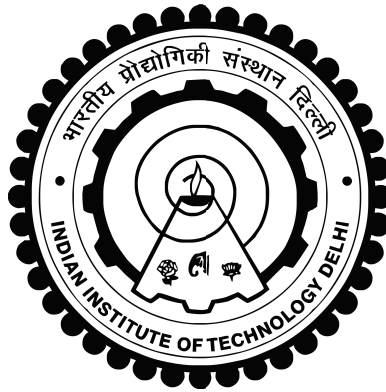


**DESIGN AND PERFORMANCE ENHANCEMENT OF
ELECTROMAGNETIC RAILGUN FOR HIGH VELOCITY LAUNCHING**

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
JUNE 2024**

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ELECTROMAGNETIC RAILGUN FOR HIGH VELOCITY LAUNCHING**

by

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Department of Electrical Engineering

Submitted

in fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the



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JUNE 2024

CERTIFICATE

This is to certify that the dissertation entitled, “**Design and Performance Enhancement of Electromagnetic Railgun for High Velocity Launching**” being submitted by **Mr. Suri Rama Naga Praneeth** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Suri Rama Naga Praneeth has completed the prerequisites for the submission of this dissertation, which, to the best of my knowledge, meets the required standard. These results have not been submitted to any other university or institute for degree consideration.

Date: June 24, 2024

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S.R.Naga Praneeth

ABSTRACT

Conventional launchers use chemical propellants to launch projectiles, where the gases expand at the bottom of the barrel and the projectile is pushed forward due to the pressure exerted by expanding gases. In the place of detonation, instead, a force generated solely by means of current can provide a lot of velocity to the projectile with improved efficiency. From this comes the question of why not electric weapons are a possible reality?

Directed energy weapons are kind of weapons that use electricity to power themselves. However directed energy can mean from particle beams to electromagnetic beams. In this category of electric weapon systems electromagnetic railguns have created their own niche because they use electric energy to power a projectile's launch. In this way railgun combines both conventional type and futuristic type weapon systems.

Appropriate metrics are derived to evaluate conventional and novel designs in rails and armatures of the railgun. In this work a railgun with a combination of narrowed rails and concave armature, that is more efficient as compared to a standard electromagnetic launcher with rectangular rails and a monolithic 'C' armature. However, it is observed that role of armature in improving the inductance gradient is minimal and the research work focused on rail design. Since tapering is improving inductance gradient, highest tapering would provide the highest improvement in inductance gradient. The result of the logic did show improvements in inductance gradient but depleted the barrel efficiency of the railgun. Hence there is a need to balance the muzzle velocity of armature, system efficiency and barrel efficiency through design changes.

From the above constraints, a new rail design of filleting is applied to improve the inductance gradient without suffering the efficiency. The question raises from this mechanical design is

whether to apply this on one side of the rail or both sides. It is observed that applying it on one side provided the flexibility to vary the fillet radius to extended limits than applying fillet on both sides. The design changes of fillet and taper, when applied together to a rail went hand in hand. The design changes helped each other by not allowing a steep taper angle and allowing highest fillet radii on outer edges. This combination provided the highest system and barrel efficiencies compared with conventional railgun design for the same amount of current input.

Apart from improving efficiency through design changes for a normal railgun, augmented railguns can also be improved by using the taper and fillet designs for the augmenting rails. To elaborate, if a railgun already exists and an extra pair of rails with taper or fillet can be added upon to the existing railgun to improve the inductance gradient by nearly 40%. Efficiency calculation require new relations for breech voltage which should consider the effects of augmenting rails. Considering the design change limits for fillet and taper, heavier loads can be easily pushed with augmented railguns with improved efficiency.

Since the current in any of the designed railguns rises abruptly, there is chance for the armature to melt or break. It has been identified that sudden application of force can create a fracture inside the armature which can be detrimental for the railgun. It hampers the multi-shot capability of railgun. Hence railguns are studied from jerk point of view and the jerk seen on armature is quantified using mathematical equations derived from inductance gradient. Tapered and filleted models are also included in the study of armature jerk along with changes in current rise time and fall time.

Most of the work performed is characterised using finite element simulations, which take long times to provide results. Hence there is a need to find a solution that can provide results of high fidelity simulation with the least possible error. Railgun is modelled as a controlled voltage source

and pulse forming network is used as a energy source to the modelled railgun and Simulink models are created. An interoperability of finite element simulations and real time simulation is established to provide quicker results.

From above discussion, it is observed that different design changes of rails of an electromagnetic railgun not only for conventional railguns but also augmented railguns are presented in this research work. Apart from it, jerk analysis with and without considering inductance gradient variation is incorporated and characterised. Moreover, interoperability of real time and finite element simulation is envisaged. Due to which, the results of high fidelity simulations of railgun can be obtained using spice models or simulink models.

सारांश

पारंपरिक लांचर प्रक्षेप्य लॉन्च करने के लिए रासायनिक प्रणोदक का उपयोग करते हैं, जहां गैसों का विस्तार होता है। बैरल के तल पर और प्रक्षेप्य दबाव के कारण आगे की ओर धकेला जाता है। गैसों का विस्तार, विस्फोट के स्थान पर, इसके बजाय, केवल करंट के माध्यम से उत्पन्न एक बल। बेहतर दक्षता के साथ प्रक्षेप्य को बहुत अधिक वेग प्रदान कर सकता है। इसी से आता है। सवाल यह है कि बिजली के हथियार एक संभावित वास्तविकता क्यों नहीं हैं?

निर्देशित ऊर्जा हथियार एक प्रकार के हथियार हैं जो स्वयं को शक्ति प्रदान करने के लिए बिजली का उपयोग करते हैं। हालाँकि निर्देशित ऊर्जा का मतलब कण किरणों से विद्युत चुम्बकीय किरणों तक हो सकता है। विद्युत हथियार प्रणालियों की इस श्रेणी में विद्युत चुम्बकीय रेलगनों ने अपनी अलग जगह बना ली है क्योंकि वे किसी प्रक्षेप्य प्रक्षेपण को शक्ति प्रदान करने के लिए विद्युत ऊर्जा का उपयोग करते हैं। इस तरह रेलगन पारंपरिक प्रकार और भविष्यवादी दोनों प्रकार की हथियार प्रणालियों को जोड़ती है।

रेलगन की रेल और आर्मेचर में पारंपरिक और नवीन डिजाइनों का मूल्यांकन करने के लिए उपयुक्त मेट्रिक्स प्राप्त किए जाते हैं। इस कार्य में संकीर्ण रेल और अवतल आर्मेचर के संयोजन वाली एक रेलगन आयताकार रेल और एक अखंड 'सी' आर्मेचर के साथ एक मानक विद्युत चुम्बकीय लांचर की तुलना में अधिक कुशल है। हालाँकि, यह देखा गया है कि इंडक्शन ग्रेडिएंट को बेहतर बनाने में आर्मेचर की भूमिका न्यूनतम है और अनुसंधान कार्य रेल डिजाइन पर केंद्रित है। चूँकि टेपरिंग से इंडक्शन ग्रेडिएंट में सुधार हो रहा है, उच्चतम टेपरिंग से इंडक्शन ग्रेडिएंट में उच्चतम सुधार मिलेगा। तर्क के परिणाम ने प्रेरण प्रवणता में सुधार दिखाया लेकिन रेलगन की बैरल दक्षता कम कर दी। इसलिए डिज़ाइन परिवर्तनों के माध्यम से आर्मेचर के थूथन वेग, सिस्टम दक्षता और बैरल दक्षता को संतुलित करने की आवश्यकता है।

उपरोक्त बाधाओं से, दक्षता को नुकसान पहुंचाए बिना इंडक्शन ग्रेडिएंट में सुधार करने के लिए फ़िलेटिंग का एक नया रेल डिज़ाइन लागू किया जाता है। इस यांत्रिक डिज़ाइन से यह प्रश्न उठता है कि इसे रेल के एक तरफ लगाया जाए या दोनों तरफ। यह देखा गया है कि इसे एक तरफ लगाने से दोनों तरफ फिलेट लगाने की तुलना में फिलेट त्रिज्या को विस्तारित सीमा तक बदलने में लचीलापन मिलता है। फ़िलेट और टेपर के डिज़ाइन परिवर्तन, जब एक रेल पर एक साथ लागू किए गए, साथ-साथ चले। डिज़ाइन परिवर्तनों ने तीव्र शंकु कोण की अनुमति न देकर और बाहरी किनारों पर उच्चतम फ़िलेट रेडी की अनुमति देकर एक-दूसरे की मदद की। इस संयोजन ने वर्तमान इनपुट की समान मात्रा के लिए पारंपरिक रेलगन

डिज़ाइन की तुलना में उच्चतम प्रणाली और बैरल दक्षता प्रदान की।

सामान्य रेलगन के लिए डिज़ाइन में बदलाव के माध्यम से दक्षता में सुधार के अलावा, संवर्धित रेल के लिए टेपर और फ़िलेट डिज़ाइन का उपयोग करके संवर्धित रेलगन में भी सुधार किया जा सकता है। विस्तृत रूप से कहें तो, यदि एक रेलगन पहले से मौजूद है और इंडक्शन ग्रेडिएंट को लगभग 40% तक सुधारने के लिए टेपर या फ़िलेट के साथ रेल की एक अतिरिक्त जोड़ी को मौजूदा रेलगन में जोड़ा जा सकता है। दक्षता गणना के लिए ब्रीच वोल्टेज के लिए नए संबंधों की आवश्यकता होती है, जिसे रेलिंग बढ़ाने के प्रभावों पर विचार करना चाहिए। फ़िलेट और टेपर के लिए डिज़ाइन परिवर्तन सीमाओं को ध्यान में रखते हुए, बेहतर दक्षता के साथ संवर्धित रेलगन के साथ भारी भार को आसानी से धकेला जा सकता है।

चूंकि किसी भी डिज़ाइन की गई रेलगन में करंट अचानक बढ़ जाता है, इसलिए आर्मेचर के पिघलने या टूटने की संभावना रहती है। यह पहचाना गया है कि अचानक बल लगाने से आर्मेचर के अंदर फ़ैक्चर हो सकता है जो रेलगन के लिए हानिकारक हो सकता है। यह रेलगन की मल्टी-शॉट क्षमता को बाधित करता है। इसलिए रेलगनों का अध्ययन झटके के दृष्टिकोण से किया जाता है और आर्मेचर पर देखे गए झटके को इंडक्शन ग्रेडिएंट से प्राप्त गणितीय समीकरणों का उपयोग करके निर्धारित किया जाता है। वर्तमान वृद्धि समय और गिरावट समय में बदलाव के साथ-साथ आर्मेचर जर्क के अध्ययन में पतला और फ़िलेटेड मॉडल भी शामिल किए गए हैं।

किए गए अधिकांश कार्यों में परिमित तत्व सिमुलेशन का उपयोग किया जाता है, जिसके परिणाम प्रदान करने में लंबा समय लगता है। इसलिए एक ऐसा समाधान खोजने की आवश्यकता है जो कम से कम संभावित त्रुटि के साथ उच्च निष्ठा सिमुलेशन के परिणाम प्रदान कर सके। रेलगन को एक नियंत्रित वोल्टेज स्रोत के रूप में तैयार किया गया है और पल्स फॉर्मिंग नेटवर्क का उपयोग मॉडल किए गए रेलगन के ऊर्जा स्रोत के रूप में किया जाता है और सिमुलिक मॉडल बनाए जाते हैं। त्वरित परिणाम प्रदान करने के लिए परिमित तत्व सिमुलेशन और वास्तविक समय सिमुलेशन की अंतरसंचालनीयता स्थापित की गई है।

उपरोक्त चर्चा से, यह देखा गया है कि इस शोध कार्य में न केवल पारंपरिक रेलगनों के लिए बल्कि संवर्धित रेलगनों के लिए विद्युत चुम्बकीय रेलगन की रेल के विभिन्न डिज़ाइन परिवर्तन प्रस्तुत किए गए हैं। इसके अलावा, प्रेरकत्व ढाल भिन्नता पर विचार किए बिना और उसके बिना झटका विश्लेषण को शामिल और चित्रित किया गया है। इसके अलावा, वास्तविक समय

और परिमित तत्व सिमुलेशन की अंतरसंचालनीयता की परिकल्पना की गई है। जिसके कारण, स्पाइस मॉडल या सिमुलिक मॉडल का उपयोग करके रेलगन के उच्च निष्ठा सिमुलेशन के परिणाम प्राप्त किए जा सकते हैं।

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LIST OF ABBREVIATIONS

EMRG	Electromagnetic Railgun
FEM	Finite Element Method
FEA	Finite Element Analysis
FE	Finite Element
PFN	Pulse Forming Network
RT	Real-Time
VSE	Velocity Skin Effect
EM	Electromagnetic

LIST OF SYMBOLS

C_o	Capacitance of Pulse forming network (F)
V_1	voltage of pulse forming network's capacitor (V)
L_o	Inductance of pulse forming network (H)
R_{sw}	Resistance of thyristor switch during ON state (Ω)
R_c	Resistance of cable (Ω)
R'	Resistance gradient (Ω/m)
L'	Inductance gradient (H/m)
x	Position of projectile
v	Velocity of projectile
a	acceleration of projectile
m	mass of projectile