Feasibility study of linear-rotary magnetic propulsion (LIRO) for next generation aircraft catapult systems on aircraft carriers

Section 1: Introduction: Technological evolution of aircraft carrier launch systems

This section sets the historical and technological background of aircraft catapults, framing the transition from early mechanical systems to the current EMALS as a response to the increasing demands of naval aviation. It will be emphasized that each technological leap was driven by the need to launch progressively heavier, faster and structurally more sensitive aircraft.

1.1 From mechanical assistance to steam power

The history of assisted launch systems on warships is one of continuous innovation, driven by the rapid evolution of aeronautical technology. The first forms of catapults, used in the early 20th century, were ingenious but relatively primitive mechanical devices. These included spring-operated systems similar to those used by aviation pioneer Samuel Langley, and weight-and-pulley mechanisms used by the Wright brothers to assist takeoff over limited distances.1 The US Navy experimented extensively developing air-based catapults, which resulted in the first launch of a person from a US Navy system on July 31, 1912.1 Later, other sources of power were explored, including gunpowder and flywheels, culminating in the launch of a Martin MO-1 observation seaplane from the USS Langley in 1924 using a gunpowder-powered catapult.1

During World War II, hydraulic catapults became standard on most aircraft carriers.1 These used a pulley system to multiply the movement of a hydraulic piston, but their performance was intrinsically limited by the strength of the cables used.3 With the advent of the jet age in the late 1940s, the limitations of hydraulic systems became critical. Unlike propeller-driven aircraft, which generated lift at low speeds through the flow of air created by the propellers over the wings, jet engines produced no such flow, requiring much stronger acceleration and over a shorter distance to reach takeoff speed.3

The revolutionary solution came in the form of the steam catapult, a British invention developed in the 1950s and quickly adopted by the US Navy.3 This technology, which has defined aircraft carrier operations for over 60 years, has proven exceptionally reliable, with aircraft carriers equipped with four such systems having at least one operational catapult 99.5 percent of the time.4 However, the steam catapult had fundamental shortcomings. It was a massive, inefficient system (only 4–6% efficient) and, most importantly, it operated without feedback loop control.4

This lack of real-time control often led to large and unpredictable force transients that could damage the aircraft's structure or reduce its service life, a problem identified by naval engineers as the system's "major shortcoming".4

1.2 The emergence of EMALS: The digital era of aircraft launch

In direct response to the limitations of steam-powered systems, the Electromagnetic Aircraft Launch System (EMALS) was developed, described as "the newest aircraft carrier catapult technology in 60 years".7 EMALS represents a paradigm shift, replacing the steam driven mechanical piston with a linear induction motor.4

This system was designed to specifically address the inherent flaws of steam catapults. EMALS provides much smoother and more controlled acceleration, significantly reducing stress on aircraft structures.4 With an energy efficiency estimated at 90%, it is clearly superior to the steam system.4 Moreover, its flexibility enables the launch of a much wider spectrum of air platforms, from heavy fighters to light unmanned drones, an essential capability for modern air groups.7

Its adoption on aircraft carriers of the class *Gerald R. Ford* of the US Navy and its planned integration on the future French aircraft carrier (PANG) reinforces EMALS' status as the current gold standard and global benchmark for aircraft launch technology.4 The success of EMALS lies not only in its power, but in the transition from raw, uncontrolled force to precise, digitally managed acceleration. The history of catapults can be seen not just as a race for more power, but as a continuous search for ever greater control and precision. Early systems were essentially ballistic launchers. The steam catapult introduced rudimentary control by adjusting the steam volume, but it remained an open-loop system. EMALS marked a fundamental leap towards closed-loop digital control based on real-time feedback. This evolutionary trajectory sets an extremely high standard for any new technology, which must demonstrate superior or at least equivalent controllability.

1.3 Research imperative: Introduction of LIRO technology

In this context of continuous evolution, this report aims to carry out a preliminary feasibility study for a radically different propulsion concept: Linear-Rotary (LIRO) technology, as a potential future alternative to EMALS.

LIRO is a new system that uses permanent magnets arranged on a rotating shaft to generate linear motion, in fundamental contrast to the electromagnetic induction principle of EMALS.12 The objective of this report is to rigorously analyze the theoretical advantages and, more importantly, the immense engineering challenges of adapting this new technology to the extreme demands of aircraft carrier catapult operations. The analysis will assess whether LIRO's mechanical architecture can provide a viable alternative to the electronic complexity of EMALS, while maintaining or exceeding the performance, reliability and control standards set by the current system.

Section 2: EMALS Architecture: An in-depth analysis of electromagnetic induction launching

This section provides a detailed technical deconstruction of the EMALS system, serving as a benchmark for evaluating the LIRO concept. Emphasis will be placed on the interaction between the four main subsystems and how they collectively achieve a controlled and high-energy launch.

2.1 Propulsion principle: The linear induction motor (LIM)

At the heart of the EMALS system is a linear induction motor (LIM), which can be conceptualized as a conventional rotary induction motor "rolled out" in a planar form.13 The specific EMALS configuration consists of a 300-foot (91 m) long launch rail composed of a stator consisting of electromagnetic coils.13 When these coils are energized in sequence, they generate a progressive magnetic wave that travels along the track.13

The mobile element is a carriage (shuttle) containing a metal armature. The magnetic wave from the stator induces eddy currents (Foucault) in this armature. The interaction between these induced currents and the magnetic field of the stator generates a Lorentz force that propels the cart forward at a very high speed.8 An essential design feature, intended to minimize reactive power losses and maximize efficiency, is that only the section of coils in the immediate vicinity of the trolley is energized at any one time.13

2.2 Power source: The energy storage subsystem

A fundamental challenge in the design of EMALS was the management of power demand. A single launch requires a massive burst of electricity, on the order of megawatts, far exceeding the ship's continuous generation capacity.13 The solution to this problem is a complex energy storage subsystem composed of four high-inertia disc alternators that essentially work like mechanical flywheels.4

The duty cycle is ingenious: in a 45-second recharge period, the ship's electrical network accelerates these massive rotors to 6,400 revolutions per minute, storing an immense amount of kinetic energy.4 During the launch, which lasts only 2-3 seconds, this stored kinetic energy is quickly converted back into an electrical impulse of colossal power.13 Each rotor can store up to 121 MJ, giving the system a total capacity of 484 MJ. This value is significantly higher than that of a steam catapult, which generates about 95 MJ, allowing the launch of heavier aircraft.4

2.3 The translator: The power conversion subsystem

The power conversion subsystem acts as a critical interface between the energy storage subsystem (which, as the alternators slow down, produces a DC-like output) and the linear induction motor (which requires a precisely controlled alternating current). The key component of this subsystem is a cycloconverter.13

This power electronic device synthesizes a frequency and voltage controlled alternating current waveform, increasing, from the energy released by the disc alternators.13 Precise control of this waveform is essential as it allows the EMALS system to finely manage the aircraft's acceleration profile, ensuring a smooth launch tailored to the specific requirements of each platform.

2.4 The Brain: The closed-loop control system

Perhaps the most important advantage of EMALS over steam catapults is its sophisticated, closed-loop control system.16 Hall effect sensors are integrated along the launch rail, which constantly monitor the position and speed of the cart with extreme precision.13

Data collected in real time by these sensors is transmitted back to the control system. It compares the actual performance to the pre-programmed launch profile and constantly adjusts the power sent to the LIM coils to maintain a constant and precise thrust on the aircraft.13 This real-time feedback loop is the mechanism that guarantees smooth acceleration, eliminates damaging shocks and minimizes stress on the aircraft structure, increasing its safety and service life.4

A fundamental analysis of the EMALS architecture reveals that its core engineering challenge lies not only in the linear motor itself, but in the sophisticated handling of high-power electrical pulses. The system is essentially a complex power electronics solution where the LIM serves as the final actuator in a chain of fast and controlled energy storage and conversion. To simplify EMALS to "a linear motor" is to ignore its central innovation: the management of megawatt power pulses. This perspective provides a critical lens through which any competing technology must be viewed: Does it simplify the fundamental problem of power management, or does it merely move it into another realm, such as the mechanical?

Section 3: LIRO (linear-rotary) technology: A new paradigm in linear propulsion

This section technically introduces and deconstructs the LIRO system, based on the descriptive documents and the patent. The aim is to present a clear, physics-based understanding of its operating principles, establishing a theoretical foundation for the benchmarking and feasibility assessment to follow.

3.1 Basic principle: Mechanical generation of a progressive magnetic wave

The heart of the LIRO system is a long, rotating shaft (1).12 A series of identical, ring-shaped permanent magnets (2) are fixed along this shaft. The arrangement of these magnets is the central innovation of the technology: the polarity axis of each magnet is ±120° out of phase with that of its neighbors.12

When this shaft is set in motion by a simple motor, the physical rotation of these out-of-phase magnets generates a *progressive (sliding) magnetic field* which moves linearly along the axis of the shaft.12 In essence, the system mechanically mimics the progressive magnetic wave generated electronically by a three-phase linear motor, but without requiring complex high-power stator windings or a continuous electrical supply to generate the field.12 The magnetic field generated along the motion axis (z) behaves as a progressive wave, described mathematically by the equation:

$$B(z,t)=B0\sin(\lambda 2\pi z-\omega st)$$

where $B0$ is the maximum intensity of the field, λ is the wavelength, ωs is the angular velocity of the shaft, z is the position and t is the time.12

3.2 Propulsion and control mechanism

The movable element (5), or shuttle, is equipped with its own set of permanent propulsion magnets (4).12 The propulsive force is generated by the interaction between the traveling magnetic wave from the rotating shaft and the magnetic fields of the magnets on the shuttle. This interaction creates a continuous "push-pull" force that propels the shuttle linearly along the shaft.12

The control philosophy is theoretically straightforward and elegant. The linear speed of the shuttle (vs) is directly proportional to the angular speed of the shaft (ωs), according to the relation $vs=2\pi\omega s\lambda$.12 Therefore, precise control of the shuttle's acceleration and final speed is theoretically achieved by precisely controlling the rotational speed of the drive motor. This transfers the control complexity from the management of high power electrical pulses (as in EMALS) to the precise management of the dynamics of a rotating mechanical system.

3.3 Frictionless operation: The levitation system

To provide guidance and support, the LIRO system uses two parallel guide rails (7) that run along the main shaft.12 The shuttle is equipped with additional permanent guide magnets (9) at its extremities, which are oriented to corresponding guide magnets (10) mounted on the rails.12

These sets of magnets are oriented to create a constant repulsive force. This force causes the shuttle to levitate between the rails, eliminating mechanical contact and therefore friction.12 This aspect promises extremely high mechanical efficiency and minimal component wear.

3.4 System architecture and energy pathway

The energy model of LIRO is fundamentally different from that of EMALS. Propulsion and levitation forces are provided by permanent magnets and do not require a continuous supply of electricity to be maintained.12 The only electrical power required continuously is that for the small motor that turns the central shaft.

This architecture fundamentally changes the energy paradigm: from a high-power impulse system (EMALS) to a mechanical system with low continuous power and high torque.12 The basic concept of LIRO technology is *the transduction of continuous, low-power rotational motion into high-force linear motion*. The system effectively uses the permanent magnet assembly as a mechanical "gearbox" or "force amplifier". This is a profound architectural difference from EMALS, which directly converts electrical energy into linear force. This distinction is not just one of implementation, but represents two fundamentally different philosophies of energy conversion. While EMALS is based on the electronic control of an actively generated field, LIRO is based on the mechanical control of a pre-existing field, inherent in the magnets.

Section 4: Comparative technical analysis: LIRO vs. EMALS

This section performs a direct, point-by-point comparison of the two systems, based on the technical details established in Sections 2 and 3. The analysis is structured to highlight the fundamental trade-offs in design philosophy, complexity, and operational characteristics.

4.1 Force generation and propulsion principle

- **EMALS:** It uses electromagnetic induction. It requires a massive, pulsed electric current through the stationary stator coils to induce a field and drive a passive armature.13 Force is actively generated and controlled electronically in real time, allowing for fine adjustments throughout the launch.
- **LIRO:** It uses the interaction between permanent magnets. It is based on the progressive magnetic wave mechanically generated by a rotating set of permanent magnets acting on another set of permanent magnets.12 Force is inherent in magnets; the system controls *speed* of the force field, not its instantaneous intensity.

4.2 Energy and power architecture

- **EMALS:** A pulsed energy system with very high power peaks. It requires a complex and massive energy storage subsystem (disc alternators) to isolate the ship's grid from extreme power demands.4 The efficiency of the system is high (about 90%), but its power requirements during launch are immense.4

- **LIRO (Theoretical):** A mechanical system with low continuous power and high torque. It eliminates the need for massive electrical energy storage and high power conversion electronics. The main consumer of energy is the motor that turns the shaft. The overall energy efficiency of the system could be extremely high due to the absence of electrical resistance losses in the propulsion mechanism and frictionless levitation.12

4.3 Control philosophy and precision

- **EMALS:** It uses a sophisticated, high-speed, closed-loop feedback system. Hall effect sensors provide real-time data, enabling dynamic and precise adjustments to the launch profile to maintain a constant traction force.13 This is a mature and proven control strategy for high precision movements.
- **LIRO (Theoretical):** Primarily an open-loop system, where the linear speed is a direct function of the rotational speed of the shaft.12 Achieving the smooth and constant acceleration needed to launch an aircraft would require an exceptionally precise and powerful control system for the rotating shaft, capable of handling immense rotational inertia and overcoming any vibration or torque ripples.17 A closed-loop system could be added, but it would control a massive mechanical element, not an electronic pulse.

4.4 System complexity and physical footprint

- **EMALS:** Characterized by *electrical and electronic complexity*. It involves extensive high power wiring, large power converter cabinets and the massive installation of under deck disc alternators.4 However, the launch rail itself is relatively simple mechanically.
- **LIRO (Theoretical):** Characterized by *mechanical and material complexity*. It replaces complex electronics with a very long (approx. 100m) high-precision rotating shaft loaded with thousands of powerful, perfectly aligned magnets. The system would also require robust bearings, a powerful drive motor with a high-precision gearbox, and the parallel guide rail system.12 The footprint below the deck for the power electronics would be drastically reduced, but the mechanical systems on and immediately below the flight deck would be much more complex.

The table below summarizes these fundamental differences, providing a clear picture of the architectural and operational trade-offs between the two technologies. This structure allows for a quick understanding of the basic dichotomies: pulsed electric vs. continuous mechanical, electronic vs. complexity mechanical complexity and closed-loop electronic control vs. mechanical speed regulation. These distinctions are central to the feasibility assessment that follows.

Characteristic	Electromagnetic Aircraft Launch System (EMALS)	Linear-Rotary Catapult (LIRO) (Theoretical)
Propulsion principle	Linear induction motor (LIM) with energized stator coils 13	Progressive magnetic wave from rotating permanent magnets 12
Main energy pathway	Ship grid -> kinetic storage -> power converters -> LIM 13	Ship grid -> motor/gearbox -> rotating shaft 12
Energy storage	Four high-inertia disc alternators (flywheels) 4	N/A (propulsive force is inherent to permanent magnets)
Control mechanism	Closed loop feedback system with Hall effect sensors monitoring the shuttle 13	Shaft rotation speed control (probably requiring its own complex feedback system) 17
Key components	Stator rail, shuttle armature, power conversion subsystem, energy storage units 13	Rotating shaft with ring magnets, shuttle with drive magnets, drive motor, guide rails 12
Friction	Minimum (shuttle on rail)	Near Zero (Magnetic Levitation) 12
Power requirement	Very high peak power (megawatts) during 2-3s launch 13	Reduced continuous power for the shaft motor; very high torque required for acceleration 19
Material dependency	Copper windings, power electronics, specialty steels 20	High performance rare earth permanent magnets, high strength shaft materials 12
Main domain of complexity	Electrical and power electronics	Mechanics and material science

Section 5: Feasibility assessment: Critical engineering challenges for a LIRO-based catapult

This section forms the core of the analysis, moving from theoretical description to a rigorous assessment of the ability of the LIRO concept to survive the physical realities of operations on an aircraft carrier. Each subsection addresses a potential failure mode or monumental engineering obstacle.

5.1 Challenge 1: Thrust generation and magnetic field limitations

- **Reference Requirement:** An EMALS system is designed to generate a maximum thrust of about 1.3 MN to launch a ~24 ton aircraft at 100 m/s on a 100 m track, which corresponds to an average acceleration of 5g.22 This is the benchmark that any alternative system must meet or exceed.
- **Feasibility of LIRO:** The force generated by a LIRO system is a function of the magnetic field gradient and the magnetic moment of the propulsion magnets.12 The critical analysis focuses on a fundamental question: Can a system based on permanent magnets, even the strongest Neodymium-Iron-Boron (NdFeB) magnets, achieve such immense force densities over a length of 100 m?
- **Critical Analysis:** There are physical limits to magnetic field strength 23, and practical tensile strength is significantly affected by factors such as air gaps and material composition.24 To generate 1.3 MN, the number, size and quality of magnets required would be unprecedented. It would require thousands of high-performance magnets, perfectly aligned and integrated into an extremely robust mechanical structure. Achieving the required tractive force represents a monumental, and perhaps insurmountable, materials and engineering challenge, being the first and major obstacle to feasibility.

5.2 Challenge 2: Strength of materials I - Demagnetization under extreme forces

- **Operating Environment:** A catapult launch is an event of extreme mechanical violence. The entire structure is subjected to immense shocks, vibrations and high acceleration forces.25
- **Failure mode:** A critical vulnerability of permanent magnets is their susceptibility to demagnetization under the influence of mechanical shocks.26 This phenomenon occurs when physical forces are strong enough to disrupt the precise alignment of the magnetic domains within the material, resulting in a permanent loss of magnetic properties.28
- **Critical Analysis:** NdFeB and Samarium-Cobalt (SmCo) magnets, although strong, are brittle materials. The repeated shock loading typical of thousands of launches per day

from an aircraft carrier would constitute an extreme fatigue environment. Even a minor loss of a few percent of magnetism in a fraction of the magnets could create force imbalances along the rail, compromising launch consistency and safety. Magnetic integrity is non-negotiable and the risk of progressive degradation under repeated shocks is a primary and critical risk factor for the LIRO concept.

5.3 Challenge 3: Strength of materials II - Corrosion in the marine environment

- **Operating environment:** An aircraft carrier operates in one of the most corrosive environments on Earth, constantly exposed to salt fog, high humidity and temperature fluctuations.
- **Failure mode:** NdFeB magnets, the strongest available, are notoriously susceptible to corrosion due to their high iron content.30 Corrosion not only physically degrades the magnet, but also causes a loss of magnetic force.33
- **Attenuation vs. reality:** Although there are protective coatings (Nickel, Epoxy, Plastic), their long-term durability under the combined onslaught of corrosion, high temperatures and extreme vibrations is questionable.31 An alternative, SmCo magnets, offer superior corrosion resistance, but are more brittle and have a lower magnetic energy product, making it even more difficult to achieve the required pulling force.34
- **Critical Analysis:** This presents a critical trade-off: use the strongest magnets (NdFeB) and risk catastrophic failure due to corrosion, or use more resistant magnets (SmCo) and likely fail to meet force requirements. Designing an encapsulation system for thousands of magnets that is perfectly sealed, structurally sound, and maintainable would be an immense design and manufacturing challenge.

5.4 Challenge 4: Rotational dynamics of a long-inertia shaft

- **Mechanical system:** A LIRO catapult would require a shaft about 100 meters long, loaded with tons of magnets, spinning at high speeds to launch an aircraft in 2-3 seconds. The rotational inertia of this assembly would be colossal.
- **Engineering obstacles:**
    - **Critical speeds:** Any long rotating shaft has critical speeds at which harmonic vibrations can lead to catastrophic failure. Designing a 100m shaft system to operate safely in its required RPM range would be a formidable task.37
    - **Torque and acceleration control:** The drive motor and gearbox would have to deliver enormous torque to accelerate the massive shaft from rest to launch speed and then potentially decelerate it, all with microsecond precision to ensure

    a smooth launch profile for the aircraft. This level of control over a mechanical system with such high inertia is a significant challenge.17
    - **Structural integrity and bearings:** The shaft would require numerous high-precision bearings along it, all perfectly aligned and capable of withstanding the immense forces and vibrations during operation. Structurally designing the shaft itself to prevent torsion and bending over its 100m length is a non-trivial problem.18

5.5 Challenge 5: Braking and system integration

- **Shuttle deceleration:** After releasing the aircraft, the EMALS shuttle is quickly stopped and controlled using a reversed electromagnetic field in a dedicated braking section of the rail. This stops a shuttle weighing about 2.6 tons.6
- **LIRO Braking Problem:** How would a LIRO system brake its shuttle? Reversing the rotation of the massive shaft is probably too slow and energy inefficient. A separate braking system (either magnetic or mechanical) would be required, adding complexity and another potential point of failure.
- **Integrate:** Integrating a massive, high-speed rotating mechanical system into the confined spaces of an aircraft carrier's hull presents significant structural and safety challenges compared to the relatively static LIM rail of EMALS.

The feasibility of a LIRO catapult is not one problem, but a *cascade of interrelated challenges on the critical path*. A failure in any of the domains (materials, dynamics, control) renders the entire system inoperable. Moreover, the solutions to these problems are often contradictory. For example, to solve the pulling force problem, the strongest magnets (NdFeB) must be used. However, choosing NdFeB magnets directly exacerbates the corrosion problem. To mitigate corrosion, SmCo magnets could be chosen, but this makes the pulling force problem more difficult to solve. Regardless of magnet choice, adding mass to increase structural robustness and withstand shocks exacerbates the challenges of rotational dynamics by increasing inertia. This web of interconnected and conflicting design constraints, where solving one problem exacerbates another, is the system's Achilles heel.

Section 6: Conclusion and recommendations for future research

This final section summarizes the findings of the entire report, providing a conclusive judgment on the feasibility of LIRO technology for this application and outlining a clear path for any future investigation.

6.1 Summary of findings: A tale of two complexities

The analysis revealed a fundamental compromise: LIRO proposes replacement *electrical complexity and power electronics to* EMALS with an extreme level of mechanical *and material science complexity*.

On the one hand, the theoretical merits of LIRO are attractive: the potential for greater energy efficiency, the elimination of massive pulsed power systems, and a simplified electrical architecture. On the other hand, these merits are overshadowed by the formidable and probably insurmountable challenges identified in Section 5: achieving sufficient pulling force, ensuring magnet survival (against demagnetization and corrosion), and managing the complex rotational dynamics of a 100-meter shaft.

6.2 Final feasibility verdict

Based on current material technology and engineering principles, the implementation of LIRO as a primary catapult for aircraft carriers **is not feasible**.

The risks associated with magnet failure under operational conditions on an aircraft carrier are too great to be acceptable in a safety-critical application. The challenges of controlling the rotational dynamics of the proposed system are beyond the scope of current, proven engineering solutions for a system of this scale and with the required reliability requirements. The mechanical complexity of LIRO, while elegant in theory, introduces multiple and interdependent failure modes that are arguably more difficult to mitigate than those in the electronic domain of EMALS.

6.3 Recommendations for future research

Despite the negative verdict for the catapult application, the novelty of the LIRO concept deserves recognition. It is recommended that research focus on applications with less extreme environmental and performance requirements, where its advantages (energy efficiency, absence of sparks, electrical simplicity) could be exploited.

A structured and incremental research program is proposed to address the fundamental questions raised in this report:

1. **Materials Science:** Conducting shock and vibration tests at high g-forces on various encapsulated rare earth magnets to quantify the mechanical demagnetization threshold. Development and testing of novel hermetically sealed multilayer encapsulation techniques for long-term survival in marine environments.
2. **Small scale prototyping:** Design and build a small-scale (eg 1-5 meters) LIRO demonstrator. The goal would not be high speed, but to validate the physics of the

mechanically generated progressive magnetic wave and study the control dynamics of a high-inertia rotating shaft.

3. **Dynamic modeling and simulation:** Development of advanced finite element analysis (FEA) models to simulate the complex interplay of magnetic forces, structural stresses and rotational dynamics in a full-scale LIRO system. This would allow virtual testing of different shaft designs, bearing placements and control algorithms to identify and mitigate resonant frequencies and vibrations.

Only by systematically addressing these fundamental challenges on a smaller and more controllable scale can it be determined whether LIRO technology has a future in high power linear propulsion applications.

Works Cited

1. Aircraft catapult - Wikipedia, accessed August 27, 2025, https://en.wikipedia.org/wiki/Aircraft_catapult
2. Catapults Come of Age | Proceedings - October 1954 Vol. 80/10/620 - U.S. Naval Institute, accessed August 27, 2025, https://www.usni.org/magazines/proceedings/1954/october/catapults-come-age
3. Armaments & Innovations - The Steam-Powered 'Cat' | Naval History Magazine, accesată pe august 27, 2025, https://www.usni.org/magazines/naval-history-magazine/2016/december/armaments-innovations-steam-powered-cat
4. Electromagnetic Aircraft Launch System - Wikipedia, accessed August 27, 2025, https://en.wikipedia.org/wiki/Electromagnetic_Aircraft_Launch_System
5. Electromagnetic catapult - Wikipedia, accessed August 27, 2025, https://en.wikipedia.org/wiki/Electromagnetic_catapult
6. EMALS – An Electrifying Launch System - SP's Naval Forces, accesată pe august 27, 2025, https://www.spsnavalforces.com/story/?id=416
7. U.S. Navy Catapult Anniversary Highlights Strides in Carrier Aviation - The Sextant, accesată pe august 27, 2025, https://usnhistory.navylive.dodlive.mil/Recent/Article-View/Article/2686602/us-navy-catapult-anniversary-highlights-strides-in-carrier-aviation/
8. ELECTROMAGNETIC AIRCRAFT LAUNCHING SYSTEM - IRJMETS, accessed August 27, 2025, https://www.irjmets.com/uploadedfiles/paper//issue_5_may_2023/37996/final/fin_irjmets1684748835.pdf
9. The Ford-class Carrier's EMALS Catapult Is Changing Naval Aviation - The National Interest, accesată pe august 27, 2025, https://nationalinterest.org/blog/buzz/the-ford-class-carriers-emals-catapult-is-changing-naval-aviation
10. Electromagnetic Aircraft Launch System (EMALS) | NAWCAD Lakehurst - NAVAIR, accessed August 27, 2025,

https://www.navair.navy.mil/lakehurst/product/Electromagnetic-Aircraft-Launch-System-EMALS

11. Electromagnetic Aircraft Launch System (EMALS) - NAVAIR, accessed August 27, 2025, https://www.navair.navy.mil/product/Electromagnetic-Aircraft-Launch-System-EMALS
12. LIRO - Vasile-Marius Oprea, accessed August 27, 2025, https://marius-oprea.ro/liro/
13. Engineering:Electromagnetic Aircraft Launch System - HandWiki, accessed August 27, 2025, https://handwiki.org/wiki/Engineering:Electromagnetic_Aircraft_Launch_System
14. Training in 60 Seconds: Rotary & Linear Motion (Part 3) - YouTube, accessed August 27, 2025, https://www.youtube.com/watch?v=GKPHJtkFZBE
15. The electromagnetic rail aircraft launch system, Pt 1: Objectives and principles, accesată pe august 27, 2025, https://www.eeworldonline.com/electromagnetic-rail-aircraft-launch-system-objectives-principles/
16. Are Electric Launches the Future of Navy Aircraft? - Tech Insights - EEPower, accesată pe august 27, 2025, https://eepower.com/tech-insights/are-electric-launches-the-future-of-navy-aircraft/
17. US8909427B2 - Control system for rotating shaft - Google Patents, accessed August 27, 2025, https://patents.google.com/patent/US8909427B2/en
18. Vibration control of a continuous rotating shaft employing high-static low-dynamic stiffness isolators | Request PDF - ResearchGate, accesată pe august 27, 2025, https://www.researchgate.net/publication/303690216_Vibration_control_of_a_continuous_rotating_shaft_employing_high-static_low-dynamic_stiffness_isolators
19. Rotation and Work-Energy Principle - HyperPhysics, accessed August 27, 2025, http://hyperphysics.phy-astr.gsu.edu/hbase/rotwe.html
20. Study on a long primary moving-magnet type linear electromagnetic catapult | Request PDF, accesată pe august 27, 2025, https://www.researchgate.net/publication/286593170_Study_on_a_long_primary_moving-magnet_type_linear_electromagnetic_catapult
21. Permanent Magnets & Assemblies | High-Performance Magnets, accessed August 27, 2025, https://www.arnoldmagnetics.com/permanent-magnets/
22. Design and Simulation of a Permanent-Magnet Electromagnetic Aircraft Launcher - Scholar Commons, accesată pe august 27, 2025, https://scholarcommons.sc.edu/cgi/viewcontent.cgi?article=1002&context=elct_facpub
23. What is the strongest magnetic field possible? Is there a limit? - West Texas A&M University, accesată pe august 27, 2025, https://www.wtamu.edu/~cbaird/sq/2014/08/21/what-is-the-strongest-magnetic-field-possible-is-there-a-limit/
24. Understanding Pull Force | Neodymium Magnets - totalElement, accessed August 27, 2025, https://totalelement.com/blogs/about-neodymium-magnets/what-does-pull-force-mean
25. Magnetic catapult to space? - NASA Spaceflight Forum, accessed August 27, 2025, https://forum.nasaspaceflight.com/index.php?topic=11909.0

26. www.hsmagnets.com, accessed August 27, 2025, https://www.hsmagnets.com/blog/top-causes-of-demagnetization-in-permanent-magnets/#:~:text=Mechanical%20Demagnetization%3A%20This%20happens%20when,be%20considered%20before%20any%20evaluation.
27. Top Causes of Demagnetization in Permanent Magnets, accessed August 27, 2025, https://www.hsmagnets.com/blog/top-causes-of-demagnetization-in-permanent-magnets/
28. How much impact force is necessary to affect a typical permanent magnet? - Reddit, accesată pe august 27, 2025, https://www.reddit.com/r/AskPhysics/comments/190gj8v/how_much_impact_force_is_necessary_to_affect_a/
29. Top Causes of Demagnetization of Permanent Magnets, accessed August 27, 2025, https://www.duramag.com/techtalk/magnet-design/causes-demagnetization-permanent-magnets/
30. How to Prevent Magnets against Corrosion - Stanford Advanced Materials, accesată pe august 27, 2025, https://www.samaterials.com/blog/how-to-prevent-magnets-against-corrosion.html
31. Regular Surface Treatment of Neodymium Magnets, accessed August 27, 2025, https://www.stanfordmagnets.com/regular-surface-treatment-of-neodymium-magnets.html
32. Neodymium Magnets in Aquariums and Saltwater - totalElement, accessed August 27, 2025, https://totalelement.com/blogs/about-neodymium-magnets/neodymium-magnets-in-aquariums-and-saltwater
33. Will Neodymium Magnets Lose Strength Over Time?, accessed August 27, 2025, https://www.hsmagnets.com/blog/will-neodymium-magnets-lose-strength-over-time/
34. appliedmagnets.com, accessed August 27, 2025, https://appliedmagnets.com/blog/rare-earth-magnets-vs-neodymium/#:~:text=Corrosion%20Resistance,-Another%20area%20where&text=In%20contrast%2C%20samarium%20cobalt%20magnets,corrosive%20substances%20is%20a%20concern.
35. How Strong Are Rare Earth Magnets? - Elements by Visual Capitalist, accesată pe august 27, 2025, https://elements.visualcapitalist.com/how-strong-are-rare-earth-magnets/
36. Samarium Cobalt Magnets Best Uses | Bunting-DuBois, accessed August 27, 2025, https://www.magnetapplications.com/blog/what-are-the-best-uses-for-samarium-cobalt-magnets
37. DYNAMICS OF ROTATING SHAFTS - DTIC, accessed August 27, 2025, https://apps.dtic.mil/sti/tr/pdf/AD0726218.pdf
38. Avoiding problems with high speeds in a rotating shaft system - Empowering Pumps, accesată pe august 27, 2025, https://empoweringpumps.com/shimmelstein-avoiding-problems-with-high-speeds-in-a-rotating-shaft-system/

39. Robustness of the Active Rotary Inertia Driver System for Structural Swing Vibration Control Subjected to Multi-Type Hazard Excitations - MDPI, accesată pe august 27, 2025, https://www.mdpi.com/2076-3417/9/20/4391