The future of propulsion is not in spinning faster — but in interacting smarter.

Electric Drive Architectures for Linear-Stroke Marine Propulsion
Rotary Conversion vs. Direct Linear Electromagnetic Actuation

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This paper should be read as a focused engineering companion to the broader framework introduced in *Phase-Structured Marine Propulsion*.

Abstract

The broader concept of **Phase-Structured Marine Propulsion** proposed in the companion paper reframes marine thrust generation not as a single continuous propulsive act, but as a sequence of distinguishable hydrodynamic phases through which force is introduced into water, transferred, sustained, and adapted as operating conditions change. Within that broader framework, the present paper addresses one of its central enabling problems: the design of the electric drive architecture required to produce controlled linear-stroke actuation across those changing propulsion phases.

The transition from rotational to linear-stroke marine propulsion introduces a fundamental redefinition of the electric-drive problem. While electric power generation is well understood and widely scalable, the challenge lies in coupling that power efficiently into a reciprocating hydrodynamic propulsor operating across a broad envelope of thrust and stroke-frequency conditions. The question is therefore not merely how to electrify propulsion, but how to shape electric motion so that it remains compatible with phase-dependent thrust requirements in water.

This paper examines two principal architectures: (1) rotary electric motors coupled to linear-stroke propulsors through mechanical transmission systems, and (2) direct linear electromagnetic drives producing reciprocating motion intrinsically. Each approach presents distinct advantages and constraints rooted not only in mechanical design, but also in dynamic response, inertial penalties, controllability, and material limitations.

The paper argues that the viability of linear-stroke marine propulsion depends less on the mere availability of electric power than on the ability to manage motion transformation, mass acceleration, and hydrodynamic coupling as a unified system. In that sense, electric-drive architecture is not a secondary implementation detail of phase-structured propulsion, but one of its central engineering determinants.

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1. Introduction

The concept of **Phase-Structured Marine Propulsion**, developed in the companion paper, departs from one of the deepest assumptions in marine engineering: that propulsion should be understood primarily as continuous rotational forcing applied to water through a propeller. In its place, the earlier paper proposed a different interpretive framework, one in which propulsion is viewed as a structured interaction between machine motion and the surrounding fluid across multiple operating phases. Under this view, thrust generation is not a single homogeneous event. It is a staged hydrodynamic process whose requirements change from startup to acceleration, from low-speed force transfer to higher-speed sustained operation, and potentially across different media and mission profiles.

Once propulsion is seen in that phase-structured way, the electric-drive problem must also be reformulated. The question is no longer simply how to power a marine device electrically. It becomes how to produce and control the specific kind of reciprocating motion required by a linear-stroke propulsor so that thrust remains effective across changing hydrodynamic phases.

This shift is not merely geometric. It alters the structure of the entire propulsion chain, from power generation to thrust delivery. In conventional marine systems, the dominant assumption is that electric motors produce rotary output and that this output is naturally compatible with propeller-based propulsion. In a linear-stroke architecture, however, the final propulsive act is no longer rotational. The system must instead generate force-dense, frequency-adaptive reciprocating motion, and it must do so in a way that remains responsive to changing thrust demands imposed by the water.

This paper therefore focuses on the electric engine as a critical subsystem within the larger phase-structured propulsion concept. Its purpose is not to restate the full hydrodynamic argument of the main paper, but to examine the two principal electric-drive paths that might make such a propulsion system physically realizable. The first uses a rotary electric motor with a transmission architecture that converts rotation into reciprocation. The second seeks to eliminate that intermediate conversion by using direct linear electromagnetic actuation.

In both cases, the central engineering challenge is the same: not simply producing power, but shaping motion so that it can serve a non-rotational propulsion regime whose operational demands vary with phase, speed, and hydrodynamic loading. The feasibility of phase-structured marine propulsion will depend in no small measure on whether this electric-drive problem can be solved with sufficient efficiency, robustness, and control.

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2. Reframing the Electric Propulsion Problem

In conventional propulsion systems, motion transformation follows a well-established sequence. In internal combustion engines, energy is first released as reciprocating piston motion. That motion is then converted into rotation through a crankshaft and subsequently transmitted to a propeller. The entire system is optimized to transform **linear impulse into continuous angular motion**.

Electric propulsion reverses this logic. The most efficient and mature electric machines are rotary motors, designed to produce continuous rotational output. When such motors are used in a linear-stroke propulsion system, the direction of transformation must be inverted. Instead of converting linear motion into rotation, the system must convert rotation into controlled reciprocation.

This inversion is not trivial. It introduces new constraints in timing, synchronization, and load response. Most importantly, it forces the system to operate across a wide dynamic range. At startup, the propulsor must generate high initial thrust to overcome inertia and static hydrodynamic resistance. As velocity increases, the system must shift toward higher stroke frequencies to maintain effective interaction with the moving water mass.

The result is a propulsion problem defined not by peak power, but by **adaptive motion control across changing regimes**.

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3. Rotary Electric Motor with Linear Conversion

The first architectural approach builds on the strengths of existing electric propulsion systems. A rotary electric motor serves as the primary power source, and its output is converted into reciprocating motion through a mechanical transmission system.

This approach benefits from the high efficiency, reliability, and power density of modern rotary motors. It also leverages decades of development in motor control, cooling, and energy management. However, the introduction of a conversion stage between rotation and linear motion becomes the central engineering challenge.

The transmission system must perform several simultaneous functions. It must convert continuous rotation into reciprocating motion with minimal energy loss. It must maintain precise control over stroke amplitude and frequency. It must respond dynamically to changing hydrodynamic loads as the vehicle accelerates. And it must do all of this without introducing excessive mechanical complexity, wear, or vibration.

Unlike traditional crankshaft systems, which operate within relatively narrow frequency ranges, the linear-stroke propulsion system demands **broadband adaptability**. The same mechanism must operate efficiently at low-frequency, high-force conditions and at high-frequency, lower-amplitude regimes.

In this architecture, the transmission is not a secondary component. It becomes the defining element of system performance. Its design determines whether the inherent advantages of electric propulsion can be preserved through the conversion process.

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4. Direct Linear Electromagnetic Drive

The second architectural approach eliminates the need for motion conversion entirely. In this configuration, the electric engine itself produces reciprocating motion through electromagnetic interaction, forming a direct linear drive.

Conceptually, this alignment between actuator and propulsor is elegant. The system avoids intermediate mechanical stages and allows for direct control of stroke dynamics. It also opens the possibility for fine-grained modulation of motion, potentially enabling advanced propulsion strategies such as phase-adaptive thrust or waveform shaping.

However, this approach introduces a different and potentially more severe constraint: **inertial inefficiency**. In a direct linear electromagnetic system, the moving elements of the motor must be accelerated and decelerated during each stroke. These elements often include magnetic materials and structural components that are significantly heavier than their rotary counterparts.

As stroke frequency increases, the energy required to reverse this mass becomes substantial. A significant portion of input energy may be consumed not in producing useful thrust, but in overcoming the inertia of the engine itself.

This creates a fundamental trade-off. The removal of mechanical transmission simplifies the system architecture but shifts the burden toward materials and mass reduction. The performance of the system becomes tightly coupled to the ability to minimize reciprocating mass while preserving electromagnetic effectiveness.

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5. Materials and Structural Constraints

Both propulsion architectures converge on a common limiting factor: materials.

In the rotary-conversion approach, the transmission system must withstand cyclic loads, high-frequency operation, and continuous interaction with varying hydrodynamic forces. This requires materials with high fatigue resistance, low friction coefficients, and structural stability under dynamic stress.

In the direct linear-drive approach, the challenge is even more acute. The moving electromagnetic components must be as light as possible while maintaining high magnetic permeability and structural integrity. Conventional magnetic materials, such as steel laminations, impose significant mass penalties that limit system efficiency at high frequencies.

Advances in **ultralight magnetic composites**, novel field-coupling geometries, or alternative electromagnetic configurations may be required to overcome these constraints. At the same time, the linear propulsor itself must be constructed from high-strength, low-mass materials capable of sustaining repeated acceleration cycles in a fluid environment.

The success of linear-stroke propulsion is therefore not only a question of mechanical design, but of **materials innovation at the intersection of electromagnetics and structural engineering**.

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6. System-Level Trade-offs

The two propulsion architectures represent fundamentally different design philosophies.

The rotary-conversion system prioritizes proven components and leverages existing electric motor technology, at the cost of introducing a complex transmission stage. Its challenges are primarily mechanical and dynamic.

The direct linear-drive system aligns naturally with the propulsion geometry and offers a more integrated control framework, but it demands breakthroughs in mass reduction and electromagnetic efficiency. Its challenges are primarily physical and material.

Neither approach can be evaluated in isolation. The optimal solution may depend on the specific application, including vehicle size, operating speed, mission profile, and energy constraints. In some cases, hybrid architectures may emerge, combining elements of both approaches to balance their respective advantages.

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7. Path Forward

The development of electric drive systems for linear-stroke marine propulsion requires a coordinated effort across multiple domains.

At the mechanical level, new transmission architectures must be designed to handle variable-frequency reciprocating motion with minimal loss. At the electromagnetic level, direct linear drives must be reimagined to reduce moving mass while maintaining force density. At the materials level, advances in lightweight composites and magnetic structures must be integrated into both approaches.

Equally important is the development of control systems capable of adapting stroke dynamics in real time, responding to changes in hydrodynamic conditions, and optimizing propulsion efficiency across the full operating envelope.

This is not a single engineering problem, but a **system-level challenge**. Its solution will define whether linear-stroke propulsion remains a conceptual alternative or becomes a practical and competitive technology in marine and underwater applications.

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8. Conclusion

The companion paper on **Phase-Structured Marine Propulsion** argued that marine thrust should be understood not as a uniform continuous action, but as a structured interaction with water unfolding across distinct operating phases. The present paper shows that once propulsion is framed in that way, the electric engine can no longer be treated as a generic source of power placed upstream of the propulsor. It becomes an active participant in the propulsion concept itself, because the manner in which motion is generated, converted, and controlled directly affects whether phase-dependent thrust requirements can be met.

Seen in this broader context, the challenge of electric propulsion is not exhausted by questions of battery capacity, motor efficiency, or available electrical power. The deeper problem is how electric energy is translated into reciprocating mechanical action within a dynamic fluid environment whose demands shift from one propulsion regime to another. Rotary-conversion systems and direct linear electromagnetic engines represent two distinct responses to that problem. One relies on mature rotary technologies but introduces the difficulty of efficient motion conversion and transmission. The other aligns more naturally with linear-stroke propulsion geometry, but imposes severe requirements in moving-mass reduction, electromagnetic design, and advanced materials.

Their comparison therefore does more than identify alternative hardware paths. It clarifies the engineering conditions under which the broader phase-structured propulsion idea may become practical. If the main paper establishes the hydrodynamic logic of the propulsion concept, this paper identifies one of its most critical implementation frontiers: the architecture of the electric drive system.

For that reason, this paper should be read as a technical extension of the earlier work rather than as a separate line of inquiry. The future of phase-structured marine propulsion will depend not only on improved propulsor geometry and hydrodynamic insight, but also on the successful integration of electric-drive architecture, transmission design, control logic, and lightweight materials into a coherent system. Only at that point can the conceptual advantages of linear-stroke propulsion be tested fairly against the long-dominant rotational paradigm.