Nonlinear Magnetic and Structural Topology Optimization of SynRM Rotors

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***Abstract*—We present a simultaneous magnetic-structural topology optimization of a synchronous reluctance motor (SynRM) rotor to maximize average torque while enforcing torque ripple and rotor stiffness constraints. Nonlinear magnetic behavior is captured using cubic-spline interpolation of the $B-H$ curve of electrical steel lamination, and design-dependent centrifugal rotor loads are parameterized using density design variables. A multi-stage continuation strategy mitigates the design oscillation between torque-focused and stiffness-focused layouts. Numerical results show the trade-off between electromagnetic performance and mechanical robustness, with final design achieving up to 14% higher average torque, up to 3% lower mass, and significantly reduced torque ripple relative to the baseline design.**

***Index Terms*—Topology Optimization, Synchronous Reluctance Motor, Computational Electromagnetics, Finite Element Analysis**

I. INTRODUCTION

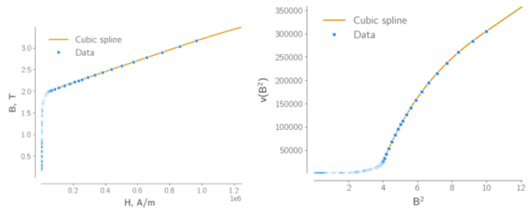
Topology optimization enables non-intuitive electromagnetic layouts, but most SynRM studies rely on linear magnetic models and neglect structural behavior, often yielding mechanically fragile designs [1], [2]. To address this, we extend a density-based framework with a nonlinear B–H constitutive model capturing saturation and a global structural compliance constraint, producing more practical rotor geometries.

A key challenge is the emergence of oscillatory designs. Torque maximization pushes material outward to strengthen flux paths, while the compliance constraint pulls material inward to reduce deformation under centrifugal loading. When applied simultaneously, these competing drivers cause the optimizer to alternate between magnetically and mechanically favored topologies. This work documents this behavior, introduces practical stabilization measures, and reports representative results that quantify the magneto-structural trade-off.

II. NUMERICAL FRAMEWORK

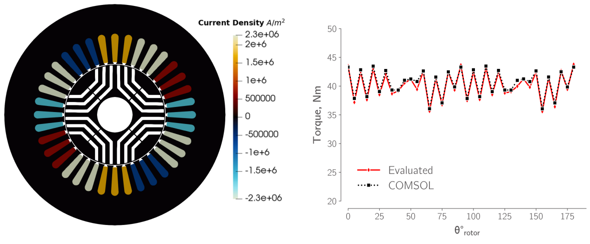
The optimization seeks a density field $\rho \in [0,1]$ for the SynRM rotor that maximizes average torque T_{avg} as follows:

$$\begin{aligned}
&\max_{\rho_e} \; T_{avg} \\
&\text{s.t. } T_{ripple} \leq T^{*}_{ripple}, \; \sum_{i=1}^{n_e} \frac{\rho_i v_i}{V_{max}} \leq v_f, \; C_{mech} \leq C^{*}_{mech} \\
&\mathbf{K}_{mag}\phi_z = \mathbf{F}_{mag} \quad \forall \quad \theta = 0°, 15°, \ldots \\
&\mathbf{K}_{mech}U = \mathbf{F}_{mech} \\
&0 < \rho_{e_{min}} \leq \rho_e \leq 1
\end{aligned} \tag{1}$$



(a) B-H curve interpolation (b) Reluctivity, $\nu(||B||)$

Fig. 1: Nonlinear B-H curve for M2 Steel using Cubic Spline



(a) Benchmark SynRM model with current density [4] (b) Torque vs. Rotor angle: Comparison with COMSOL

Fig. 2: Nonlinear Magnetostatic FEA Validation for Torque Prediction: Comparison with COMSOL

Here V_{max} is the maximum element volume, T_{ripple} is the Root-Mean-Square (RMS) to mean torque ratio, and C_{mech} is the total compliance under centrifugal loading. Material properties for magnetic reluctivity, mechanical stiffness, and load are interpolated using the RAMP scheme with continuation on penalization and Heaviside projection to promote 0/1 designs [3].

The nonlinear magnetic response of M21 electrical steel lamination is represented through cubic-spline interpolation of measured $B-H$ data. Figure 1 shows the resulting saturation curve. The finite element electromagnetic solver incorporates the resulting element-wise permeability $\mu(B)$ during field solution with a Newton–Rhapson solver for the magnetic potential ϕ_z and corresponding adjoint sensitivity analysis. The rotated projection method introduced in [4] is used to handle density filtering and rotor motion consistently. Torque prediction across rotor angle are validated against COMSOL

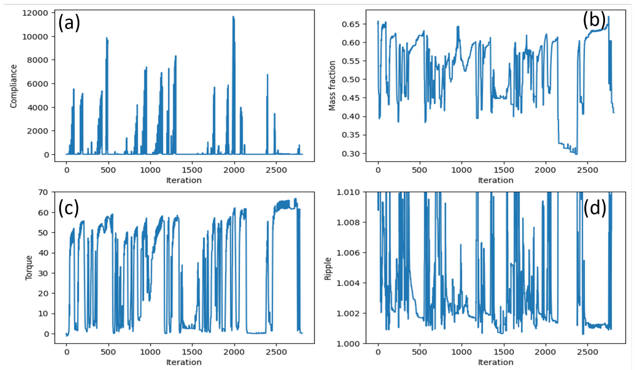
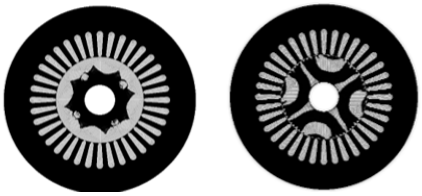


Fig. 3: Tracking a) Compliance, b) Mass fraction, c) Torque, and d) Torque Ripple across iteration. Oscillation between a high-torque/high-compliance and a low-torque/low-compliance design



(a) A stiffness-favorable design (b) a torque-favorable design

Fig. 4: Design oscillation between topologies with maximum torque and mechanical compliance constraint

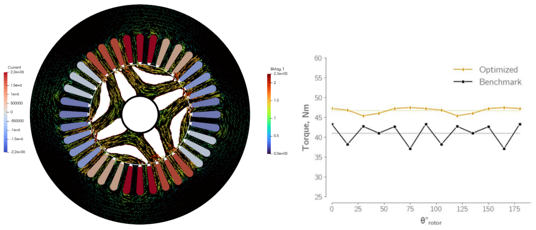
for a benchmark SynRM motor with two-pole pairs and 36 slots in Figure 2. Sensitivities for the torque objective are obtained via a consistent adjoint linearization of the nonlinear magnetic residual.

Mechanical compliance is evaluated under rotor-speed-dependent centrifugal force $f_e = \rho_e \omega^2 r_e$, where ω is the rotor speed and r_e is the radial distance of the element centroid from origin. The total compliance is given as $C(\rho)_{mech} = \mathbf{F_{mech}}^\top U$. The applied load vector, and hence, the displacement field and the compliance scale proportionally with ω^2 due to linear elasticity assumption. The Compliance sensitivities are computed through the standard adjoint method.

III. RESULTS AND DISCUSSION

A Synchronous Rotor is optimized using the formulation shown in (1) to maximize average torque output while imposing a maximum volume fraction constraint of 65% and a maximum torque ripple factor of 1.0001. The mechanical compliance of the structure is constrained to be less than $1e-3$ to obtain a stiff structure. As shown in Figure 3, enforcing all constraints simultaneously leads to oscillatory behavior between two layouts: a) a stiffness-favorable design (Figure 4(a)) where the material is pulled inward to meet compliance but reducing torque, and b) a torque-favorable design (Figure 4(b)) where the material is moved outwards, boosting torque but increasing compliance due to high centrifugal forces. The observed optimizer oscillation is not merely a numerical artifact but a manifestation of competing design gradients in coupled magneto-mechanical optimization. To stabilize the optimization, we employ a multi-stage continuation strategy as follows:

- Step 1: Loose ripple and compliance constraints (early iterations)
- Step 2: Tighten torque ripple constraints at iteration 500
- Step 3: Tighten compliance constraint at iteration 1000
- Step 4: Activate Heaviside projection at iteration 1500



(a) Final converged rotor design along with magnetic field intensity (b) Torque profile for the benchmark and the topology-optimized design

Fig. 5: Optimal rotor topology with a multistage constraint continuation approach: 3% less weight, 14% higher torque, and $10\times$ lower torque ripple than benchmark model.

The final optimal rotor design is shown in Figure 5(a). Relative to the benchmark rotor in Figure 2(a), the optimal topology has 3% less weight, 14% higher average torque, and 10 times lower torque ripple as shown in Figure 5(b). The optimizer prefers thicker ribs to ensure sufficient structural stiffness under centrifugal loads.

IV. CONCLUSION AND FUTURE WORK

We show that incorporating magnetic nonlinearity and structural compliance in SynRM topology optimization yields a mechanically viable rotors but triggers oscillation between torque-driven and stiffness-driven designs. A staged continuation strategy stabilizes this behavior by sequentially tightening constraints, producing balanced rotors that retain torque improvements while satisfying mechanical limits. The results are directly applicable to designers seeking higher-fidelity tools that jointly address electromagnetic performance and structural integrity. Future directions include formal multi-objective formulations, multi-material extensions, and electro-thermal coupling.

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