Passive force balancing of an active magnetic regenerative liquefier

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Passive force balancing of an active magnetic regenerative liquefier

Abstract
Active magnetic regenerators (AMR) have the potential for high efficiency cryogen liquefaction. One active magnetic regenerative liquefier (AMRL) configuration consists of dual magnetocaloric regenerators that reciprocate in a persistent-mode superconducting solenoid. Issues with this configuration are the spatial and temporal magnetization gradients that induce large magnetic forces and winding currents. To solve the coupled problem, we present a force minimization approach using passive magnetic material to balance a dual-regenerator AMR. A magnetostatic model is developed and simulated force waveforms are compared with experimental measurements. A genetic algorithm identifies force-minimizing passive structures with virtually ideal balancing characteristics. Implementation details are investigated which affirm the potential of the proposed methodology.

Keywords
Active Magnetic Regenerator, Gadolinium, Liquefaction, Superconducting, Genetic Algorithm

Disciplines
Materials Science and Engineering | Physics

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Passive Force Balancing of a Superconducting Active Magnetic Regenerator

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Abstract

The Active Magnetic Regenerator (AMR) is a promising technology for cryogen liquefaction, however commercially relevant performance has yet to be reported. A central issue is the rapid change of magnetization in the superconducting windings, which is exacerbated as prototypes scale in capacity. This underlying problem has been avoided by reducing magnetic field strengths and device sizes which, consequentially, has impeded the development of AMR liquefiers. To solve this problem, we present a force minimization approach using passive magnetic material to balance the magnetization of a dual-regenerator AMR. A magnetostatic model is developed and validated with experimental measurements. A genetic algorithm identifies force-minimizing passive structures with virtually ideal balancing characteristics. Implementation details are investigated which affirm the potential of the proposed methodology for AMR liquefiers.

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Keywords:  Active Magnetic Regenerator, Force Balancing, Liquefaction, Superconducting, Genetic Algorithm
Nomenclature

**Roman**
- A  area [m²]
- B  magnetic flux density [T]
- F  force [N]
- H  magnetic field strength [A m⁻¹]
- I  solenoid winding current [A]
- j  current density [A m⁻²]
- M  magnetization [A m⁻¹]
- Q  heat [W]
- r  radius [m]
- t  time [s]
- \( \mathbf{T} \)  Maxwell electromagnetic stress tensor [N m⁻²]
- T  temperature [K]
- V  volume [m³]
- z  spatial coordinate along solenoidal centerline

**Greek**
- \( \delta_{ij} \)  Kronecker delta [-]
- \( \Gamma \)  geometric factor [-]
- \( \mu_0 \)  Permeability of free space [H/m]
- \( \rho \)  density [kg m⁻³]
- \( \rho_e \)  electrical resistivity [Ωm]
- \( \sigma \)  specific magnetization [A m² kg⁻¹]
Subscripts and Superscripts

\begin{itemize}
\item C \quad \text{cold reservoir or cold side}
\item coil \quad \text{superconducting magnet winding}
\item Curie \quad \text{magnetic ordering temperature}
\item Eddy \quad \text{eddy current}
\item H \quad \text{hot reservoir or hot side}
\item m \quad \text{middle passive structure}
\item magnet \quad \text{position of AMR relative to magnet}
\item o \quad \text{outer passive structure}
\end{itemize}
1. Introduction

Although hydrogen has an energy density several times greater than fossil fuels, the low volumetric energy density of the gaseous phase has motivated research efforts on storage [1] and liquefaction technologies. The low conversion efficiencies of present state-of-the-art plants coupled with transportation losses significantly raise the cost of liquid hydrogen. The Active Magnetic Regenerator (AMR) uses a Magnetocaloric Material (MCM) as the matrix media in a thermal regenerator [2], and shows promise for high efficiency distributed cryogen liquefaction [3]. The magnetic phase change is intrinsically more reversible than vapor-compression, and the potential for small-scale distributed plants facilitate liquid hydrogen transportation infrastructure.

While room temperature AMR devices using permanent magnets are an active area of research [4, 5, 6, 7], only a small number of cryogenic AMR devices using superconducting magnets have been presented. Zimm et al. (1996) measured a 35 K temperature span while rejecting heat to liquid nitrogen. Rowe and Tura (2006) [8] measured a 50 K temperature span from room temperature using a three material regenerator, and the device was later modified for cryogenic testing [9]. The layered experiments were investigated in subsequent analytical and numerical works [10, 11, 12]. Kim et al. (2013) [13] presented a 57 K temperature span with a no-load cold temperature of 24 K using 83 grams of magnetocaloric material. The device performance was numerically investigated and an optimized layering composition was proposed [14]. While the temperature spans reported by Kim et al. approached the domain of a hydrogen liquefier, larger devices are required to provide commercially relevant capacities.
Barclay et al. (2016) [15] and Meinhardt et al. (2017) [in review] described a large-scale, superconducting AMR with an ultimate goal of hydrogen liquefaction from room temperature. While a temperature span of 100 K was reported with 2.1 kg of a single magnetocaloric material, the applied field was limited by the rapid magnetization change in the superconducting windings. Improved cooling capacities required increased magnetocaloric mass which, to avoid a magnet quench, decreased the magnetic field strength and consequently the cooling capacity; a dilemma stifling AMR liquefier development.

The interaction between magnetocaloric material and superconducting magnetic field generators must be understood. Rowe and Barclay (2002) [16] investigated magnetic forces in a reciprocating AMR. The centerline field of a static, air-bored solenoid simulation was used to evaluate magnetization and magnetic forces. An optimization routine found a flywheel configuration minimizing the cycle RMS torque accounting for magnetic, pumping and inertial loads. While a flywheel attenuates torque fluctuations at the drive input, the rapid change in magnetization exists in the superconducting winding.

Peksoy and Rowe (2005) [17] later performed magnetostatic field simulations to investigate the variation of magnetization in a single and two-material AMR. Rowe and Tura (2008) [18] continued this work by investigating ferromagnetic shims to concentrate magnetic field lines in the regenerator, demonstrating that the influence of magnetic material on the magnetic field distribution can be both the detrimental and beneficial. Arnold et al. [19] presented experimental measurements of the mechanical, eddy and magnetic work in a reciprocating AMR device. Although large forces were present, it
was found that the thermodynamic cycle work was on the order of the experimental uncertainty. This emphasized that while \textit{regenerator} efficiencies may be high, \textit{device} efficiencies are heavily penalized without force balancing.

While Peksoy and Rowe (2005) [17] solved the magnetostatics problem, several works have investigated magnetic forces with a simplified treatment of the magnetic field distribution (i.e. $\vec{B} = \mu_0 \vec{H}$). Kamiya \textit{et al.}[20] analyzed the force waveform of a reciprocating AMR with gadolinium doped dysprosium aluminum garnet using a similar methodology as Rowe and Barclay (2002) [16]. The authors reported a 60\% force reduction using magnetic material between regenerators. Allab \textit{et al.}[21] simulated the magnetic force on a gadolinium (Gd) sample as a function of the local magnetic field strength, and presented force waveforms for a magnetized and demagnetized regenerator. Gama \textit{et al.}[22] compared experiments and simulations of the force on a ferromagnetic sphere as it was brought into the air gap of a permanent magnet array. Balli \textit{et al.}[23] showed experiments and simulations of magnetic force on a magnetocaloric material using a similar formulation, and demonstrated partial force cancellation from dual regenerators in a reciprocating design.

In the present work, a magnetostatic model is developed to study the interaction of a multilayered AMR and superconducting magnetic field generator. Magnetic forces are analyzed and compared to experimental measurements. A passive ferromagnetic structure is proposed and optimized to balance magnetic forces. The contribution of each component to the total force waveform is investigated and implementation details such as force sensitivity and field distribution are discussed.
2. Methodology

2.1. Magnetostatics model

The superconducting winding is modeled in COMSOL Multiphysics using the magnetic fields interface in an axisymmetric domain. For the low operating frequency of an AMR, Maxwell’s equations reduce to

\[ \nabla \times \vec{H} = \vec{j} \]  
\[ \nabla \cdot \vec{B} = 0 \]

where \( \vec{B} \) is the magnetic flux density in T, \( \vec{H} \) is the magnetic field strength in A/m and \( \vec{j} \) is the current density in A/m². These are solved numerically with the constitutive relation \( \vec{B} = \mu_0(\vec{H} + \vec{M}) \), where \( \vec{M} \) is the total magnetic moment or magnetization in A/m.

Magnetic forces are evaluated in COMSOL Multiphysics by numerically integrating the Maxwell stress tensor

\[ \vec{F} = \oint_S \vec{T} \cdot \vec{n} \, ds \]

where \( S \) is a surface in free space enclosing the considered body and \( \vec{n} \) is a unit vector normal to the integration surface. The Maxwell stress tensor, \( \vec{T} \), is defined for any coordinate system as

\[ \vec{T}_{ij} = \frac{B_i B_j}{\mu_0} - \delta_{ij} \frac{||\vec{B}||^2}{2\mu_0} \]

where \( \delta_{ij} \) is the Kronecker delta and \( ||\vec{B}||^2 \) is the squared norm of the flux density. Björk et al. (2010) [24] and Meessen et al. (2013) [25] used this for-
mulation to evaluate forces in permanent magnet assemblies using analytical field expressions derived from Fourier series solutions of the governing partial differential equations.

If the flux density and magnetization are uniform over a material volume, and the applied field and magnetization are along the solenoidal axis, the force can be described as

$$F_z = \mu_0 M_z \frac{\partial H_z}{\partial z}$$

which is the so-called Kelvin force [26, 27]. Although the more-robust Maxwell stress tensor formulation is used in the present work, the Kelvin force familiarizes the physical mechanisms describing magnetic forces in magnetized bodies. Eq. 5 describes a force increase with field gradient and magnetization, which occur with increased coil current and decreased magnetocaloric material temperature, respectively.

2.2. AMR configuration

The AMR apparatus considered contains two regenerators with eight layers of magnetocaloric material which are summarized in Table 1. The layers consist of rare-earth gadolinium and gadolinium alloys with yttrium, terbium, erbium, dysprosium and holmium with a Curie temperature spacing of 20 K per layer. Spherical particles are prepared by AMES using a rotating disk apparatus [28] and packed into regenerators with a porosity of 0.36.

The simulations described here consider gadolinium-like materials with molecular field theory (MFT) [27, 29] generated magnetization data shifted to the respective Curie temperature. The specific magnetization ($M = \rho \sigma$)
Table 1: Rare-earth alloys synthesized by AMES laboratory for eight-layer regenerator.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Composition</th>
<th>$T_{\text{Curie}}$ [K]</th>
<th>Mass [g]</th>
<th>Diameter [mm]</th>
<th>Length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Gd$<em>{0.16}$Ho$</em>{0.84}$</td>
<td>153</td>
<td>57</td>
<td>31.8</td>
<td>14.2</td>
</tr>
<tr>
<td>L2</td>
<td>Gd$<em>{0.27}$Ho$</em>{0.73}$</td>
<td>173</td>
<td>100</td>
<td>38.1</td>
<td>17.3</td>
</tr>
<tr>
<td>L3</td>
<td>Gd$<em>{0.15}$Dy$</em>{0.85}$</td>
<td>193</td>
<td>139</td>
<td>44.5</td>
<td>17.7</td>
</tr>
<tr>
<td>L4</td>
<td>Gd$<em>{0.32}$Dy$</em>{0.68}$</td>
<td>213</td>
<td>172</td>
<td>50.8</td>
<td>16.8</td>
</tr>
<tr>
<td>L5</td>
<td>Gd$<em>{0.66}$Er$</em>{0.31}$</td>
<td>232</td>
<td>202</td>
<td>57.1</td>
<td>15.6</td>
</tr>
<tr>
<td>L6</td>
<td>Gd$<em>{0.3}$Tb$</em>{0.7}$</td>
<td>253</td>
<td>235</td>
<td>63.5</td>
<td>14.7</td>
</tr>
<tr>
<td>L7</td>
<td>Gd$<em>{0.9}$Y$</em>{0.1}$</td>
<td>274</td>
<td>258</td>
<td>69.9</td>
<td>13.3</td>
</tr>
<tr>
<td>L8</td>
<td>Gd</td>
<td>293</td>
<td>268</td>
<td>76.2</td>
<td>11.6</td>
</tr>
</tbody>
</table>

as a function of temperature and magnetic flux density is shown in Fig. 1. The magnetization is then corrected for porosity and processed into relative permeability curves.

Fixed heat rejection and absorption temperatures of 280 K and 120 K are considered, relevant for the first stage of a hydrogen liquefier or natural gas liquefaction. A linear temperature profile is assumed and the magnetocaloric effect (e.g. the influence of the magnetic field on the local temperature) is neglected, which is shown to be a reasonable assumption. Implementing the transient, field-dependent temperature requires an inner level of iteration, limiting the optimization scope with readily accessible computational resources.

The magnetic field generator in the present work is a persistent-mode, conduction-cooled NbTi Cryomagnetics 70-650-010CF superconducting solenoid as described by Barclay et al. (2016) [15]. The solenoid consists of two composite windings with the properties listed in Table 2.
Figure 1: Specific magnetization of gadolinium, $\sigma$, illustrating para-ferromagnetic phase change at $T_{\text{Curie}}=293$ K. Magnetization increases with field ($\mu_0 H$) and decreases with temperature. Vertical dashed lines indicate layer operating range.

A Futek LCM350 load cell measures the net force on the regenerator assembly as an Allen Bradley linear actuator displaces regenerators for 2 seconds with constant velocity. The measured force waveforms are corrected for the assembly weight of 0.33 kN. E-type thermocouples measure the temperature across each layer which are recorded with a National Instruments CompactDAQ.

2.3. Optimization formulation

Passive, ferromagnetic structures are proposed in the regenerator assembly to minimize the rapid change of magnetization in the windings. Fig. 2 shows the outer radii of the proposed passive structures parameterized for
Table 2: Superconducting magnet dimensions.

<table>
<thead>
<tr>
<th>Winding</th>
<th>Inner diameter [mm]</th>
<th>Outer diameter [mm]</th>
<th>Length [mm]</th>
<th>Turns [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>172.7</td>
<td>180.6</td>
<td>203.2</td>
<td>1708</td>
</tr>
<tr>
<td>2</td>
<td>180.6</td>
<td>232.9</td>
<td>203.2</td>
<td>17791</td>
</tr>
</tbody>
</table>

optimization. The passive structure between regenerators \((r_{m1}, r_{m2})\) has a fixed length of 127 mm with a 10 mm gap on either side for the layer 1 (L1) housing and flow distributor. The outer structure \((r_{o1}, r_{o2})\) has a fixed length of 85 mm, constrained by the superconducting magnet’s open-air rhetort, and is spaced 10 mm from layer 8 (L8). A fixed inner radius of 10 mm is considered in both structures, and the layer geometry is summarized in Table 1. The passive structure is composed of 1010 steel with experimental B-H data provided by COMSOL Multiphysics.

The force waveform, \(F(z_{magnet})\), is composed of static force simulations as the regenerator assembly translates downwards with increasing values of \(z_{magnet}\). An optimization problem is formulated to find the ferromagnetic structures defined by \((r_{m1}, r_{m2}, r_{o1}, r_{o2})\) that minimize the \(l^2\) norm of the force waveform.

\[
\text{Min} \| F(r_{m1}, r_{m2}, r_{o1}, r_{o2}) \| = \sqrt{\sum_{z_{magnet}=0}^{z_{max}} F(z_{magnet}, r_{m1}, r_{m2}, r_{o1}, r_{o2})^2} \quad (6)
\]

Due to the problems non-convexity, the optimization is performed in MATLAB using the genetic algorithm. An initial population of 25 randomly generated configurations are evaluated, and the 4 design candidates with the highest fitness are cloned into the next generation. Remaining design
candidates are procreated with a crossover fraction of 0.9 in a process mimicking biological evolution, amalgamating the design traits of two favorable
parents. The probability of a design procreating into the next generation increases with fitness, and designs with high forces are eliminated. Further implementation details are outlined in the MATLAB documentation. With reasonable bounds on the design variables, the optimization converges within 12 hours.
3. Results

3.1. Validation

Two experiments are performed to validate the force waveform; one with regenerators in the paramagnetic (PM) phase at $\mu_0 H = 3T$ ($I_{coil}=33.4$ A) and a second in the ferromagnetic (FM) phase at $\mu_0 H = 4T$ ($I_{coil}=44.2$ A). $\mu_0 H$ refers to the magnetic flux density without magnetic material in the magnet center. For the ferromagnetic test, liquid nitrogen boil-off is fed through the assembly to bring the regenerators to a nearly homogeneous temperature of 150 K. Fig. 3 shows the average temperatures of each layer over one cycle for the top (red) and bottom (blue) regenerators in the paramagnetic (dashed) and ferromagnetic (solid) phases. The Curie temperature of each layer is shown for reference.

![Figure 3: Measured temperatures for validation in paramagnetic (PM) and ferromagnetic (FM) phases.](image)

"Top PM" "Bot PM" "Top FM" "Bot FM" "TCurie"
Fig. 4 shows the measured and simulated force waveform using the temperature measurements in Fig. 3. The force waveform for the paramagnetic (PM) and ferromagnetic (FM) phases are shown in Fig. 4 (A) and (B), respectively. The solid black line shows the simulated waveform, while the red and blue dashed lines show experimental measurements with the linear actuator moving in the positive (→) and negative(←) directions. After the regenerator is displaced in either direction, a piston drives heat transfer fluid through the material matrix as required to complete the AMR cycle. The perturbed solid temperature invokes a magnetization change, causing the offset between red and blue curves. This manifests as the thermodynamic cycle work and serves as a limit to what can be attenuated with passive balancing.

The model is in good agreement with the magnitude of the measured force waveforms, and the peak force location is predicted for both experiments. While the simulated paramagnetic forces are nearly identical to measurements, the ferromagnetic simulations are 12.5 % higher than measured. The discrepancy is likely caused by a combination of simulated magnetization data and the magnetic alloy treatment. The MFT data in Fig. 1 shows higher ferromagnetic magnetization at low field strengths than experimental measurements [30]. Additionally, shifting gadolinium magnetization data to the ordering temperatures of layers 1-8 causes properties to be referenced 140 K from the Curie temperature, where the impact of varying alloy parameters (e.g. electron spin and orbital angular momentum) on magnetization is most pronounced [27]. This error is expected to decrease in operation with a linear temperature span from $T_H = 280$ K to $T_C = 120$ K, where materials operate in the vicinity of the magnetic ordering temperature.
Figure 4: Validation of simulated waveforms (solid black) with measurements for paramagnetic (A) and ferromagnetic (B) conditions. Red and blue curves correspond to positive and negative linear actuator velocities, where the difference yields the thermodynamic cycle work.
3.2. Force minimization

The optimization converged on a design vector of \((r_{m1}, r_{m2}, r_{o1}, r_{o2}) = (25.45, 12.66, 16.41, 23.25) \text{ mm}\) shown in Fig. 2 above, for a winding current of 66.0 A \((\mu_0 H=6 \text{ T})\) and temperature reservoirs of 280 K and 120 K. Fig. 5 shows the magnetic force on the top regenerator (solid red), bottom regenerator (solid blue), top passive structure (dashed red), middle passive structure (dashed black) and bottom passive structure (dashed blue) as the regenerator assembly is displaced between limits. While the large forces exerted on individual components requires detailed housing design, the superposition or net assembly force (solid black) is effectively reduced to zero with the proposed passive structures.
Figure 5: Force contribution from each component at $\mu_0 H=6$ T in optimized geometry. *Reg* denotes regenerator and *Pas* denotes passive magnetic material. Superposition of forces demonstrates near-ideal cancellation (Balanced Waveform).
4. Discussion

4.1. Solution Sensitivity

The passive structures are optimized for $T_C = 120$ K and $\mu_0H = 6$ T; however, the impact of operating conditions on the force waveform with passive structures must be investigated. Fig. 6 shows contours of the maximum net force as a function of $\mu_0H$ and cold side temperature for the optimized assembly, while Fig. 7 shows contours of the maximum net force with two regenerators. The contours illustrate the force variation during the transient cooling process at any field strength.

Figure 6: Contours of the simulated maximum net force as a function of the cold side temperature and flux density. Passive structures are optimized for $T_C = 120$ K and $\mu_0H = 6$ T. Hot side temperature fixed at 280 K.
Figure 7: Contours of the simulated maximum net force as a function of the cold side temperature and coil current for dual regenerator system.

Without passive balancing material, the forces increase weakly with decreasing temperature and strongly with increasing field strength as shown in Fig. 7. Fig. 6 shows the insensitivity of maximum force to field strength at the design temperature of 120 K; the same passive structure balances forces at an applied field of 3 T (33.2 A) and 6 T (66 A). Furthermore, the force is significantly reduced for nearly all operating conditions with passive balancing material.
4.2. Field homogeneity

Minimizing the low field strength is a priority, as the adiabatic temperature change of gadolinium alloys scale with $B^{2/3}$ [31]. Fig. 8 shows the centerline field distribution with a void bore (black), with magnetocaloric material (red) and with the optimized assembly (blue) for a coil current of 66 A. The regenerator locations are indicated by vertical dashed lines.

![Graph showing centerline magnetic flux density](image)

Figure 8: Centerline magnetic flux density for air, regenerators (MCM) and the optimized assembly (Pas) showing a minimal increase in low field strength with passive balancing material.

The magnetocaloric material compresses field lines in the solenoid bore, increasing the high field strength. This phenomena was observed and exploited by Rowe and Tura (2008) [18], however Fig. 8 demonstrates how the same mechanisms can also be detrimental. Fortunately, the increased low field strength is minimal with the addition of passive balancing material.
4.3. Eddy Currents

A consequence of the force balancing structure is the generation of eddy currents. The power dissipation from induced currents in an electrically resistive medium act as a parasitic load into the cold side of the AMR. Kittel (1990) [32] derived analytic expressions for eddy current power dissipation

\[ Q_{Eddy} = \frac{\Gamma AV}{32 \rho_e} (dB/dt)^2 \]  

where \( \Gamma \) is a geometric form factor, \( A \) is the area enclosed by the largest possible current loop, \( V \) is the volume of material and \( \rho_e \) is the electrical resistivity. As AMR performance increases with field strength and operating frequency, \( \Gamma AV/\rho_e \) must be minimized. While \( \Gamma AV \) can be reduced with thin laminations of the 1010 alloy considered here, powder cores [33] and tape-wound amorphous magnetic materials [34, 35] deserve further investigation.

5. Conclusion

To overcome the rapid change of magnetization in superconducting windings, a passive force balancing structure is proposed in a dual-regenerator, reciprocating AMR apparatus. A magnetostatic model is developed to investigate the interaction between magnetocaloric material and a superconducting magnetic field generator. The model is validated with experimental force measurements, and a genetic algorithm is implemented to identify a force-minimizing passive balancing structure at cold side temperature and field strength of 120 K and \( \mu_0 H = 6 \, T \).

The methodology produces a unique structure which decreases the net force by a factor of 100. The optimized structure is shown to be effective
over a wide range of operating conditions and has minimal impact on the effective magnetic field change. Future works will focus on the experimental treatment of magnetization properties, experimental testing of optimized passive structures and the minimization of low field strength.

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