An Overview of Passive Magnetic Bearings

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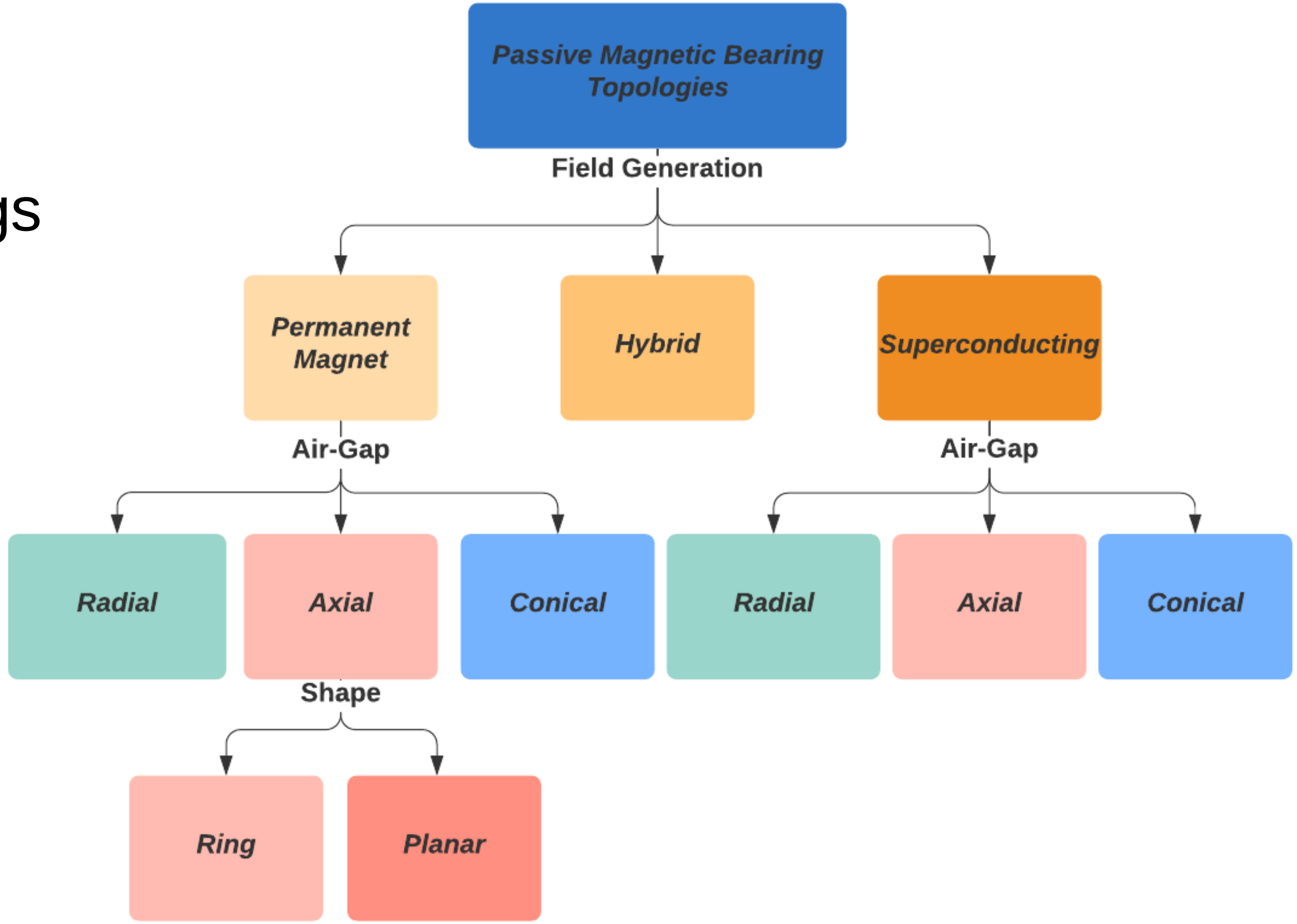
Outline

- Motivation
- Permanent Magnetic Bearings
- Superconducting Magnet Bearings
- Hybrid Solutions
- System Design
- Conclusions



Motivation

- Rotational systems need suspension systems to prevent damage [1].
- Friction losses are proportional to speed, in high-speed applications they can be very large [7].
- Permanent magnetic bearings remove this, but Earnshaw’s theorem prevents a fully passive magnetically levitated system from being stable [2].
- Ways to achieve stability include mechanical bearings [3], active control [4], superconducting or diamagnetic materials [5], or Halbach stabilization coils [6].
- When considering losses of each stable type, the combination of permanent magnetic bearings (PMB) and superconducting magnetic bearings (SMB) is desirable [7].

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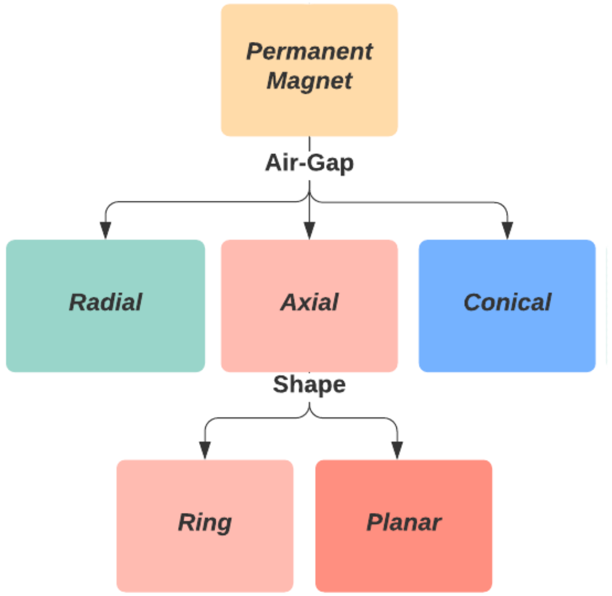
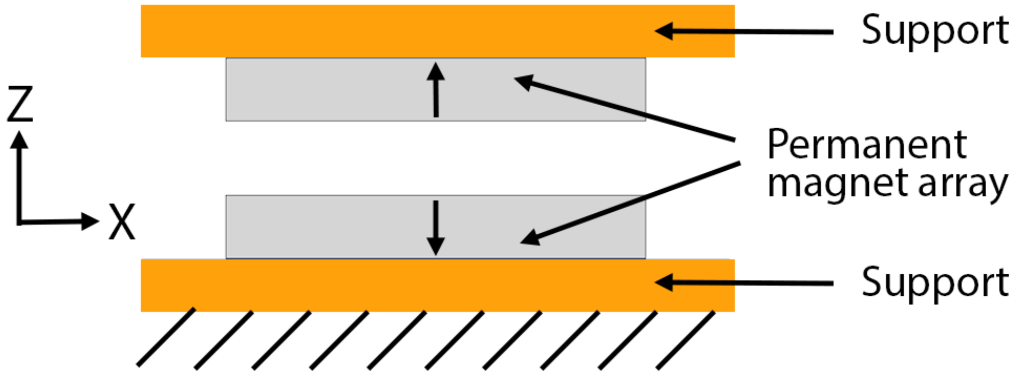
Permanent Magnetic Bearings

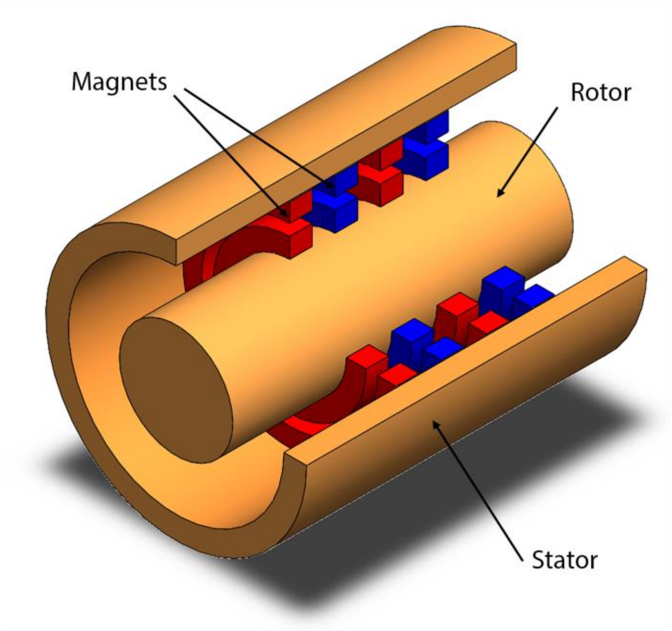
- Forces created through attraction and repulsion between permanent magnets.
- Important characteristics:
  - Materials used
  - Geometry
  - Magnetization Direction
- Optimization Criteria
  - Stiffness, force as a function of position.
  - Cost
  - Size

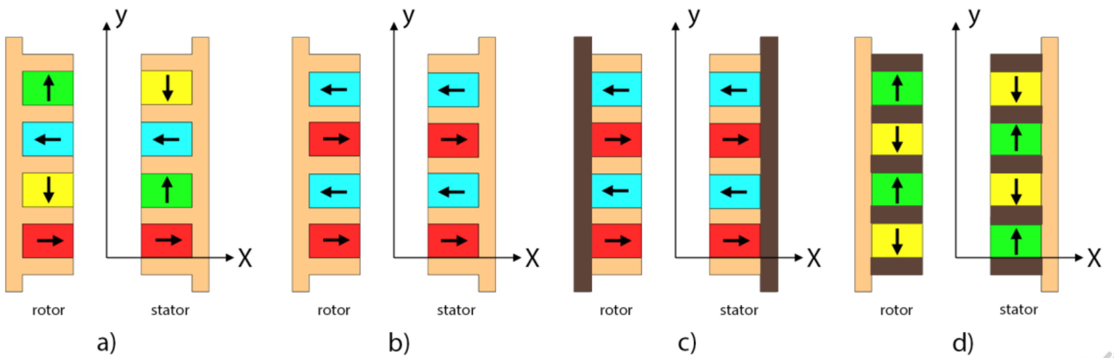




Permanent Magnetic Bearings

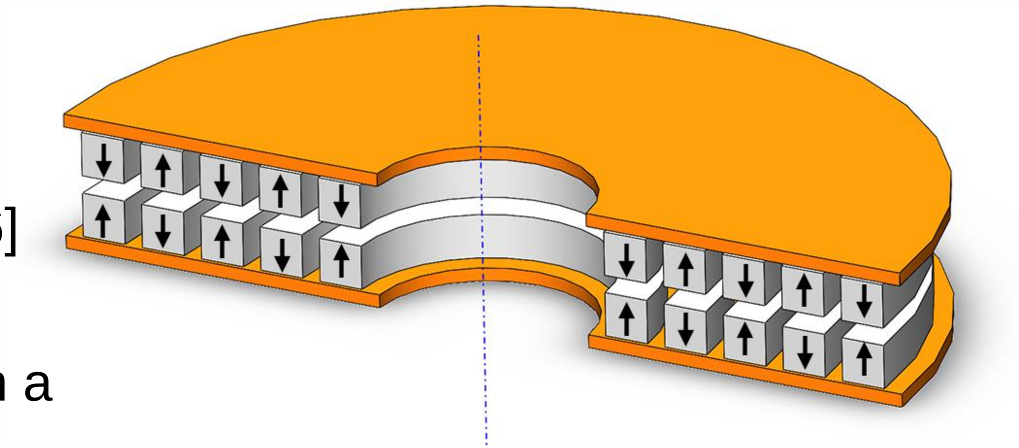
- Ring PMBs oriented Radially
  - Force generated by alignment of inner and outer materials.
  - Closed form analytical as well as FEA are common tools for geometry analysis.
  - Optimization focuses on force, stiffness in a direction, and cost.
  - Optimization results favor Halbach Arrays, particularly in conjunction with the use of back iron.





Permanent Magnetic Bearings

- PMBs oriented Axially
  - Typically located near the ends of a rotational system, often to counteract gravity [32].
  - Closed form analytical [21] as well as FEA [16] are common tools for geometry analysis.
  - Optimization focuses on force [16], stiffness in a direction [18], magnet size [16].
  - Characteristics considered for optimization: magnet size [16], magnetization [6], number of layers [21], use of back iron [21].



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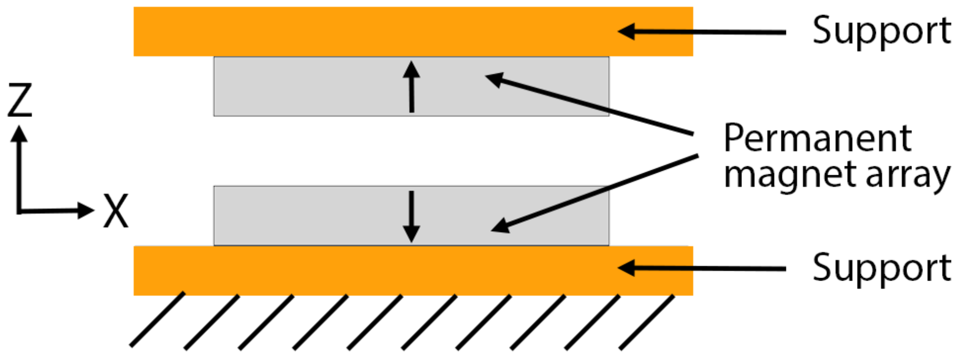
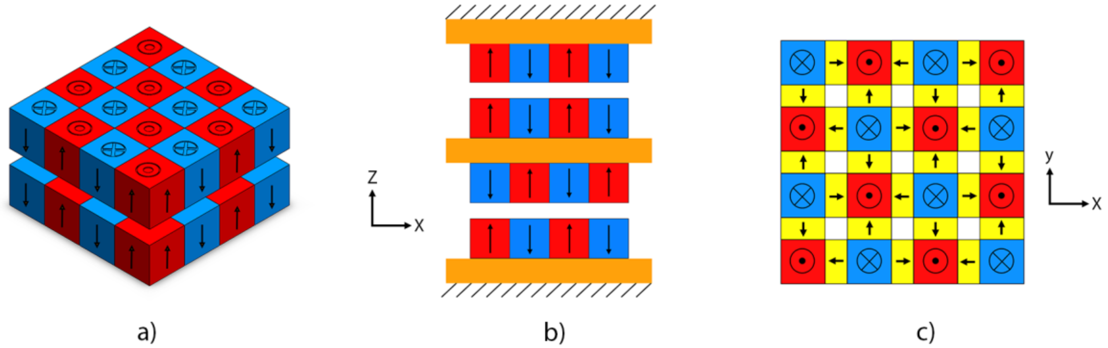
Permanent Magnetic Bearings

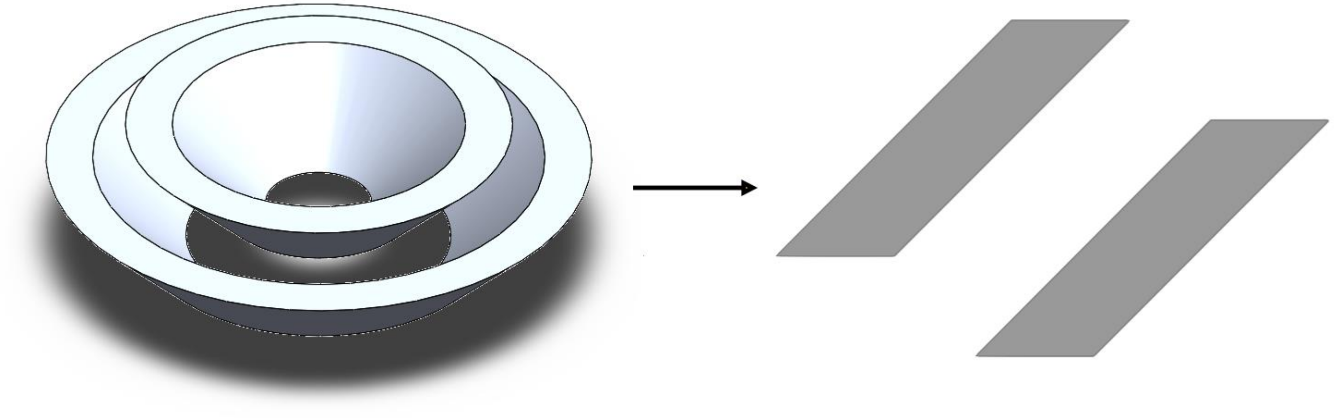
- Planar PMBs
  - Closely related to Axially Orientation in design and function.
  - Allows for more complicated 2D magnetization schemes.
  - Optimization of force generation favors Halbach Arrays.





Permanent Magnetic Bearings

- Conic PMBs
  - Based on a wrapped linear slide bearing [33].
  - Allows for flexibility in direction of force, however Earnshaw's Theorem still applies.
  - Increased complexity and manufacturing cost, especially for magnetic materials.



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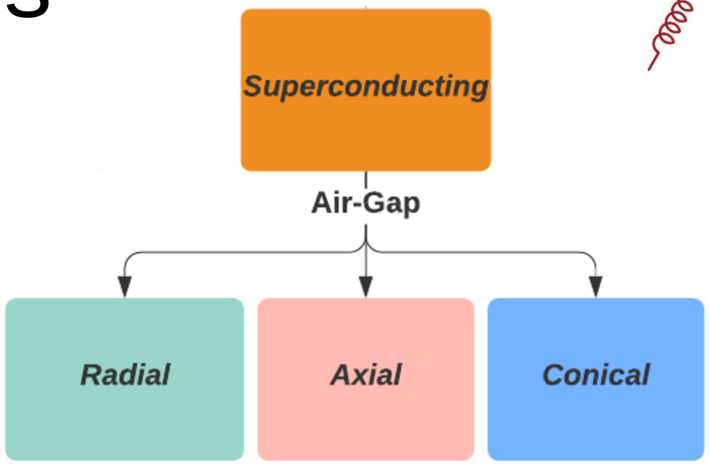
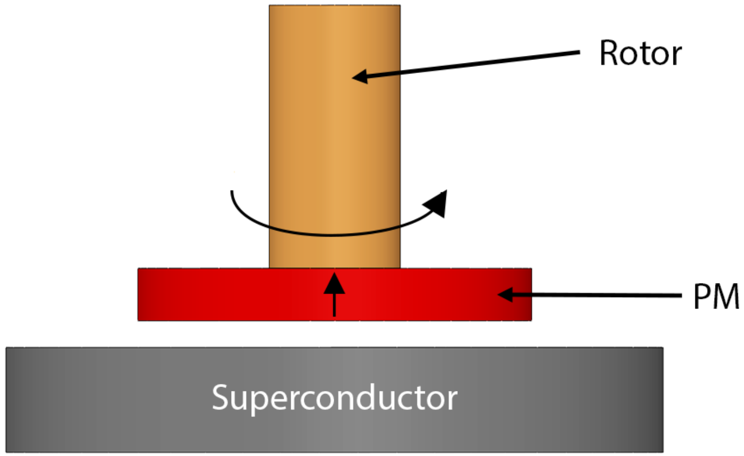
Superconducting Magnetic Bearings

- Force generation due to the Meissner effect and flux pinning [34].
- Analytical modeling done via critical-state model and Maxwell equations [35], with numerous FEA methods [36].
- Notable advantage is it can achieve stable levitation.
- Notable disadvantage is it requires cooling mechanisms to achieve superconducting states.





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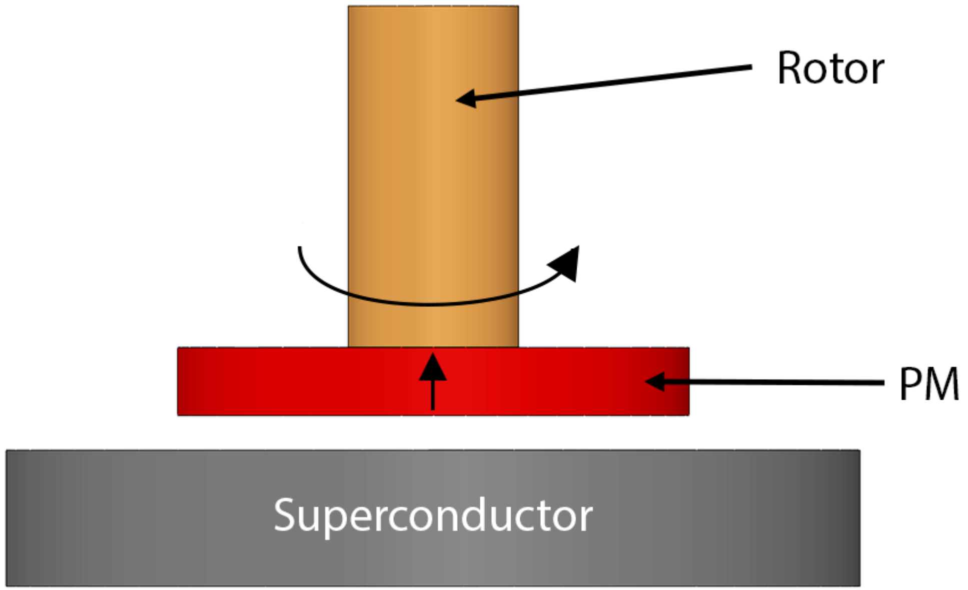
Superconducting Magnetic Bearings

- Axial SMBs
  - Similar to Axial PMB in function and are typically designed to counteract gravity.
  - Provides stabilization in axial and lateral directions while permitting rotation [44].
  - Optimized around stiffness and load capacity.
  - Optimization favors use of Halbach Arrays [46] or multipole systems [47] for the permanent magnetization scheme.



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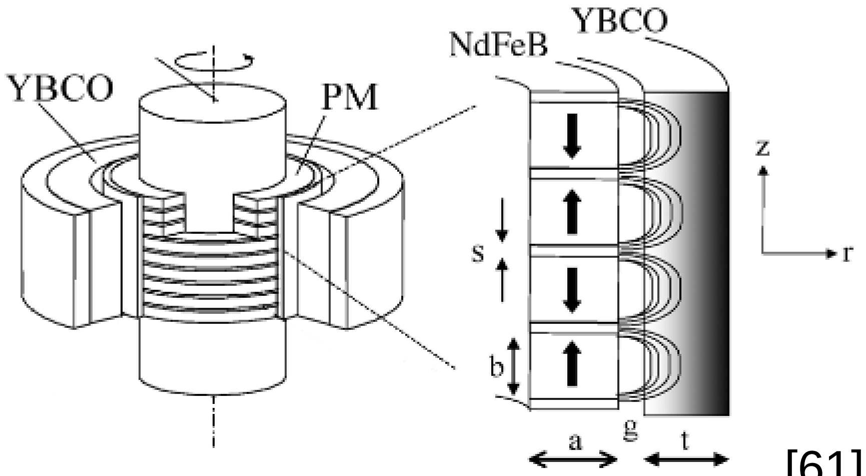
Superconducting Magnetic Bearings

- Radial SMBs
  - Contain permanent magnets on the rotor with superconducting components on the stator for ease of cooling [61].
  - Force creep is a major concern with solutions such as pre-loading and supercooling methods [62].
  - Stiffness and force optimization favor the use of iron shims between the magnets.
  - Radial stiffness typically much better than Axial SMBs, but axial stiffness is lower.



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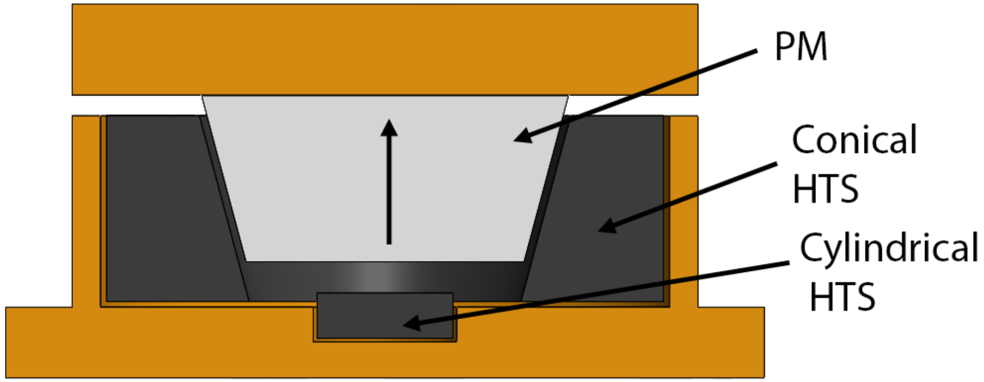
Superconducting Magnetic Bearings

- Conic SMBs
  - Allows stable force generation in multiple directions [75].
  - Increased manufacturing difficulty of both the magnetic and superconducting components.
  - Further study into dynamics is needed.



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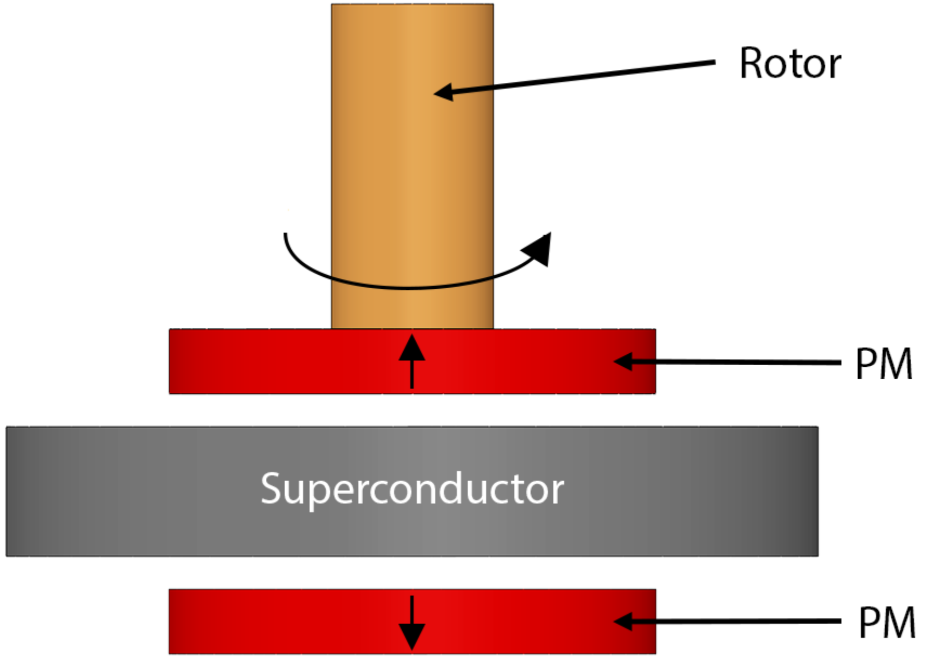
Hybrid Solutions

- Combine both PMB and SMB attributes
  - Increase force by increasing size of superconductor between the magnets.
  - If superconductor is above critical temperature force generation between magnets is still present [1].
  - Can be placed above or below rotor to counteract gravity using either attractive or repulsive force generation [76].



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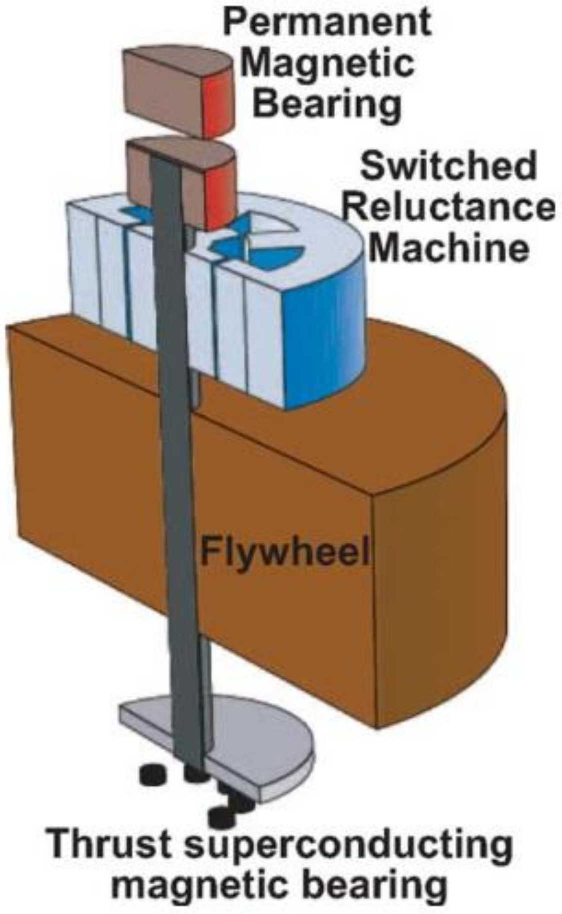
System Design

- Create system from PMB and SMB pieces
  - Combine PMB simplicity with SMB for fully passive system stabilization, typically with a traditional motor for torque production.
  - Commonly use radial PMBs or SMBs with an axial lift SMB [52], [87].
- Experimental validation in:
  - 3 kW / 5 kWh flywheel system [52]



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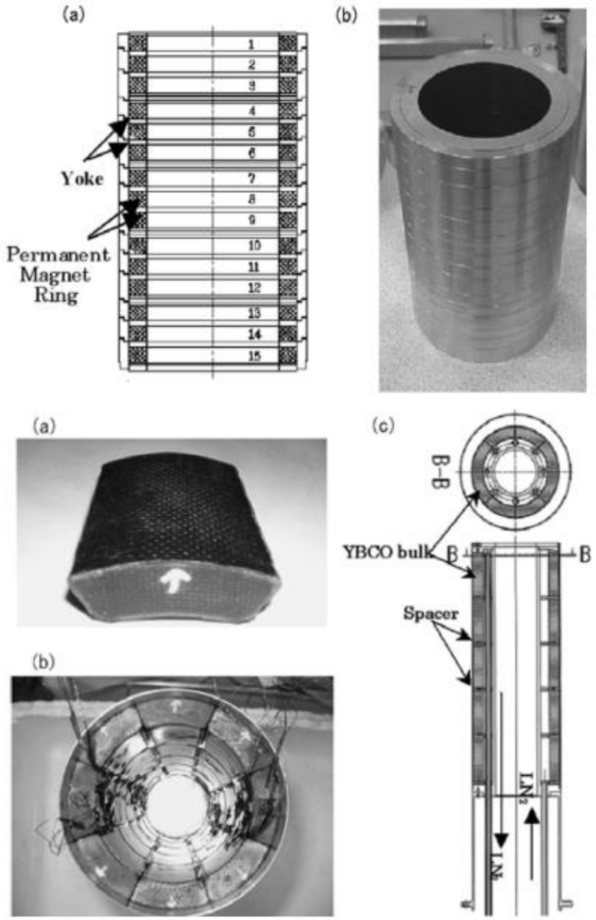
System Design

- Can also include the use of active magnetic bearings with associated losses.
- Experimental validation in:
  - 10 kWh flywheel system [57]



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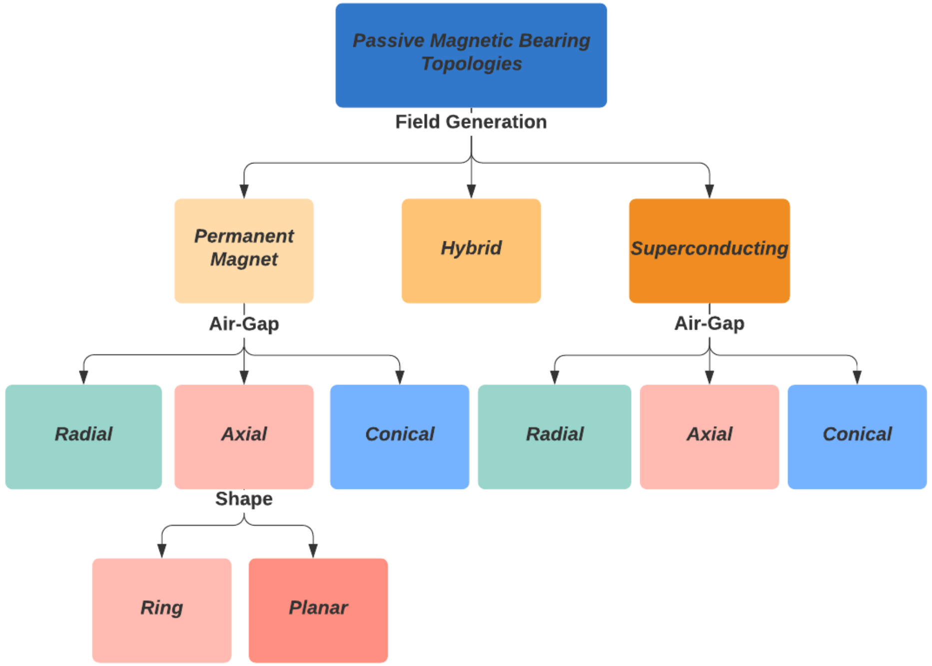
Conclusions

- Operating processes for passive magnetic bearing types are provided.
- A hierarchy of passive magnetic bearing topologies is created with examples for analysis, optimization, and where applicable recommendations for each type.
- Hybrid SMB and PMB solutions are desirable in that they can achieve both stable levitation and low losses, at the expensive of a more complicated system.



Conclusions

Thanks For Your Attention

Questions?