ME 4053: Fall 2025
Project 3
Flywheel Energy Storage Analysis

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This project analyzes the design and control for a flywheel for power grid energy storage. The goal is to understand and model trade-offs in the design of inertial energy storage components and the control system for active magnetic bearings.

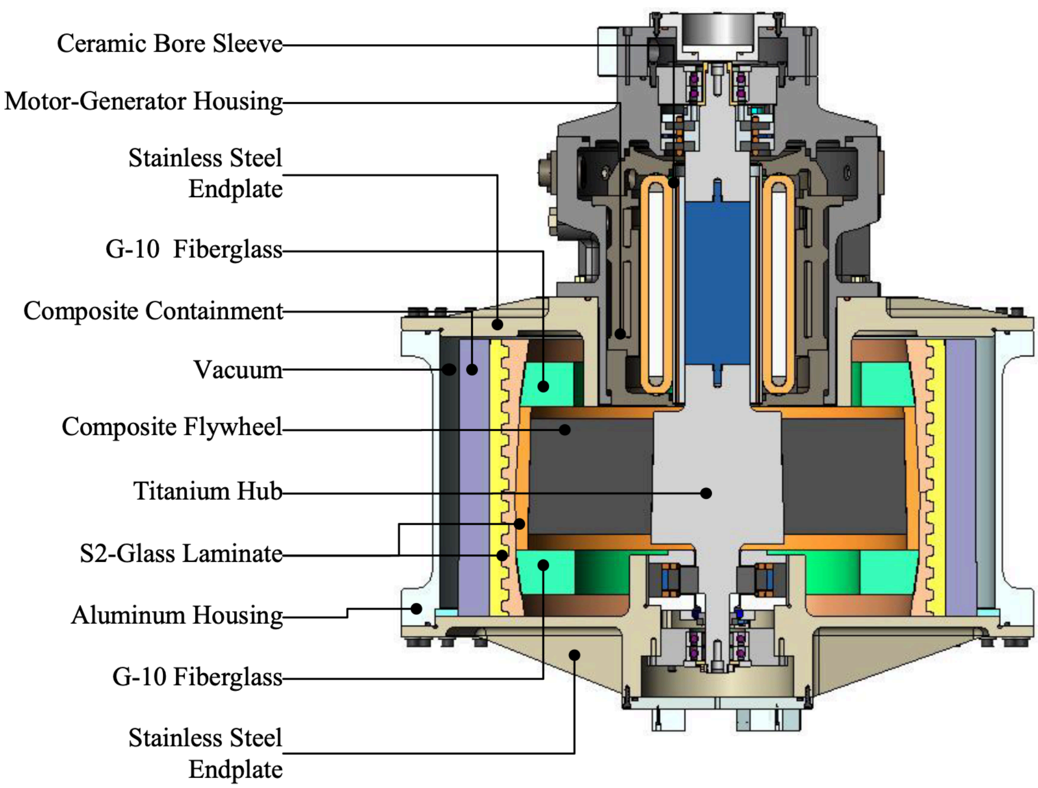

Figure 1: Example high performance flywheel energy storage system [1]

The project requires you to write MATLAB code to size the electric machine and flywheel, determine the thermal performance of the system while operating in vacuum, and tune and simulate the magnetic bearing controllers. The report is expected to be similar in depth, length, and format to the previous two projects. Since flywheel energy storage touches on topics in electrical engineering, you will interface to a

[1] M. Flynn, "A Methodology for Evaluating and Reducing Rotor Losses, Heating, and Operational Limitations of High-Speed Flywheel Batteries," PhD Dissertation, University of Texas at Austin, 2003.

remote team of electrical engineers. This team is not communicative (you can report this to them on their TEAMMATES survey), but will perform necessary, accurate, and prompt analysis for you on the electric machine components to determine losses, magnetic shear stresses, and magnetic bearing properties. You pass them information and receive their response via MATLAB functions that will be provided to you on Canvas.

1. The Flywheel System

The flywheel system will rely on a high performance carbon composite rotor, permanent magnet motor/generator, and active magnetic bearings, as shown in Fig. 2. Key parameters for the design sizing of these components are provided in Table 1. Radial magnetic bearings should be selected so that each bearing has a rated force that is twice the rotating group weight.

Figure 2: Layout of flywheel rotating group with components that need to be designed

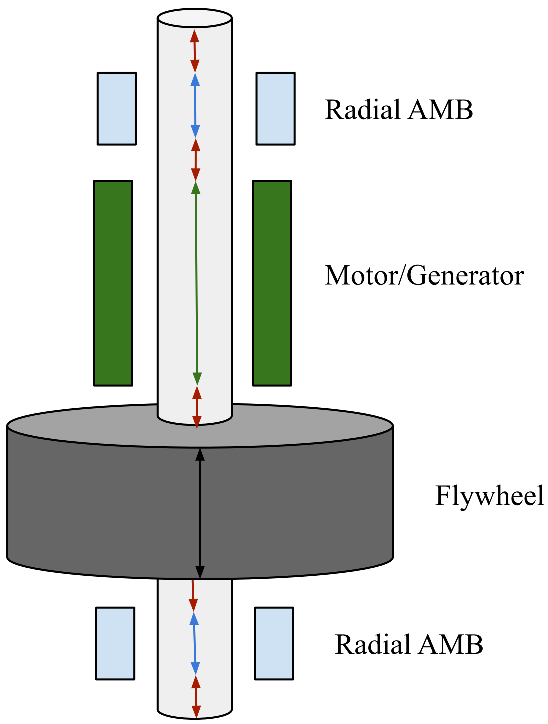

Table 1: Properties of the flywheel system

Parameter	**Value**
Axial clearances between components	20 mm
Radial clearance between flywheel and vacuum housing	20 mm
Clearance between all non-flywheel components and vacuum housing	1 mm

Max. safe steel shaft	175 m/s
Max safe PM tip speed	175 m/s
Max. safe composite flywheel tip speed	900 m/s
Mass density of composite flywheel	1600 kg/m^3
Mass density of steel	7850 kg/m^3
Mass density permanent magnets	7850 kg/m^3
Max. safe rotating group temperature	100 °C
Min. magnet thickness	2 mm
Rotor emissivity	0.4
Housing emissivity	0.9
Rotating group balance grade (ISO1940)	G2.5

This flywheel system is expected to operate down to half of its maximum speed. This means that it is at a state-of-charge (SoC) of 0% when the flywheel is rotating at half of its maximum speed and 100% when the flywheel is rotating at maximum speed.

2. The Remote Electrical Engineers

The electrical engineering team is available to perform magnetic analysis for you in real time based on your requests. As an initial offering, they will provide these MATLAB functions for you:

- `magneticShear.m`, returns average magnetic shear stress on the rotor. Input arguments:
  - Magnet thickness
  - Stator current
- `rotorLosses.m`, returns the average losses on the electric machine's rotor. Input arguments:
  - Magnet thickness
  - Rotor diameter
  - Axial length
  - Stator current
  - Rotor speed
- `statorLosses.m`, returns the average losses on the electric machine's stator. Input arguments:
  - Magnet thickness
  - Rotor diameter
  - Axial length
  - Stator current
  - Rotor speed

- `ambParameters.m`, returns complete parameter set for a desired AMB: the stiffness constant, force constant, bias current, rated control current, inductance, resistance, and axial length. Input arguments:
    - Rotor diameter
    - Force rating

See Appendix A for the detailed specification of each function, including units on the arguments and return values.

3. The Report

Your report should be from the perspective of a consulting engineer who is tasked with helping a company (eXtreme Storage Inc) develop a new flywheel energy storage product. XS has an existing "baseline" product that they developed over two decades ago and is currently used without issue by hundreds of customers. XS now needs to launch a new product for a very different energy storage cycle (power vs time command from the power grid). Unfortunately, the engineers who developed the original system have all retired, and the design know-how and analysis have been lost.

Your report will first quantify the performance of the baseline system for a standard power grid storage cycle. Next, your report will perform a design study and recommend a design for XS's new product, including a magnetic bearing control system, and compare its performance relative to the baseline design.

Similar to past projects, the report should take the form of an "executive summary;" however, this time it will be addressed to XS. Completeness, clarity and conciseness are all far more important than length. Something on the order of 6-8 pages in length is probably reasonable, the report is limited to 10 pages. The report should meet professional standards, with no grammar or spelling errors.

The report should include an introduction paragraph that enables the reader to understand what the report is about and that briefly describes the contents of the report. The report should include a conclusions paragraph that reviews the key findings of your analyses both qualitatively and quantitatively on the viability of your new system design.

A Gradescope portal will be provided for this report. The MATLAB code developed and used for this project will be submitted to a separate Gradescope portal. Since we will have your code, you do not need to include a listing of the MATLAB code in the report. However, any figures used in the report should be generated via the submitted MATLAB code.

4. The Deliverables

Your report should document the following deliverables.

1. For the baseline flywheel system specified in Appendix B:
    a. Create a plot of the losses and rotating group temperature at rated power as a function of state of charge
    b. Determine the specific power (kW/kg) and specific energy (Wh/kg) of the rotating group

c. Determine efficiency after completing the provided storage cycle, considering the amount of energy that will be needed to recover self-discharge losses assuming the flywheel starts the storage cycle with 50% SoC
d. Plot the AMB system response (current, force, rotor position) to a step force disturbance in the x direction concentrated at the location of top AMB. Show this for zero shaft rotational speed. The disturbance force magnitude should be 10% of the top AMB's rated force.
e. Create a plot of the dynamic stiffness in the radial and tilting direction for the magnetic bearing system as a function of frequency
f. Plot the rotor runout due to mass imbalance as a function of the SoC.

2. Perform a design study to find a flywheel design (objectives: minimize losses, maximize specific power, maximize specific energy) for the new storage cycle shared with your team on the course Canvas page. Your independent design variables are the magnet thickness and maximum rotational speed. All of the dimensions of the flywheel system will be based on satisfying the requirements from Section 1, including the maximum rotating group temperature, and achieving the new storage cycle. Your storage cycle is satisfied if you can start at 50% SoC and maintain an SoC > 0% throughout the complete cycle while meeting the required power.
    a. Depict and discuss trade-offs in the design space for viable designs. At a minimum, this should include a plot of specific power vs specific energy vs storage cycle efficiency (again considering the amount of energy needed to recover self-discharge losses).
    b. Select an optimal design that has comparable or improved performance relative to the baseline design. Provide dimensions for the system components and a justification for why you have selected this design.
3. Design controllers for the magnetic bearings needed for the optimal flywheel storage system you designed in problem 2 that yield comparable or improved performance relative to the baseline design.
    a. Provide transfer functions for the position and force controllers
    b. Compare the new flywheel system's AMB step response to the baseline system.
    c. Compare the dynamic stiffness and rotor runout to the baseline system.