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Rapid Iteration Optimization of Electromagnetic Actuator Design

Introduction

High-performance electromagnetic actuators have many applications ranging from automotive valve actuation to fuel injectors, yet the optimization of actuator design is not always a straightforward process, involving facets that span disparate types of analysis and software. Additionally, the design space of geometry options can be large, especially when considering multiple configurations and shapes of the armature and back-iron in addition to the basic dimensional design space. Czero developed a novel combination of tools that streamlines the process for designing and optimizing electromechanical actuators and valves quickly and cost effectively. Additionally, the automation of this process allows our engineers to iterate through hundreds of actuator designs per day to optimize metrics such as power consumption, energy consumption, maximum current, hold current, actuator speed, and mass. This paper will describe this design and optimization process, using examples from a recent project for an automotive engine valve.

Step 1: Define Performance Targets and Geometric Constraints

The essential precursor to the process is clearly defining the performance targets, geometric constraints, and valve/actuator configuration for the application; this would be required for any design effort. Performance targets and relative priority will vary by application. Some geometric constraints may be fixed by pre-existing hardware or other design decisions. The valve/actuator configuration may already be clearly defined when iterating on an existing product, or for blank-sheet designs this step could involve architecture trade studies to first determine the best valve and actuator configurations.

In Czero's recent engine valve project, multiple valve/actuator configurations were considered and evaluated via a trade study. For example, configurations included a valve that is spring-returned closed and actuated open, and a valve that is centered when un-powered and actuated both open and closed. The key performance targets were a multi-faceted list: fast travel time, low power, compact packaging, and good controllability. The compact packaging requirement led to a maximum outer diameter constraint based on the valve spacing when installed. Specific travel time requirements were obtained from 1-D engine modeling simulations. Low power was left as one of the variables to simply minimize. Additionally, a requirement for "good controllability" stemmed from the need for the actuator to be able to respond quickly (i.e. fast current rise time), and with sufficient force at any point of the valve stroke to be able to influence the valve's motion. This requirement started as subjective, but quickly evolved to become quantitative once the optimization process was underway.

Step 2: Explore design space of actuator geometries

Within the geometric constraints, many actuator parameters remain to be optimized, such as number of axial and radial turns and wire gauge of the coil, pole diameter, armature shape, and location and number of armature/backiron gaps. Where possible, known relationships are used to minimize the number of independent variables. For example, it is known that the cross-sectional area of the magnetic flux path should be constant, so that can be used to calculate the back-iron OD for a given ID, or vice versa. For each of several primary geometric shapes, a single part can be used to generate hundreds of configurations exploring the design space. Using SolidWorks this is accomplished via a design table. By exporting the sketch points, each of these actuator configurations is ready for the next step: import into a magnetic finite element program for evaluating its magnetic properties. The initial set of configurations may use a coarse discretization of each parameter to explore as wide a design space as possible while keeping computation expense low. Subsequent runs typically use finer discretization to hone in on promising regions of the design space.

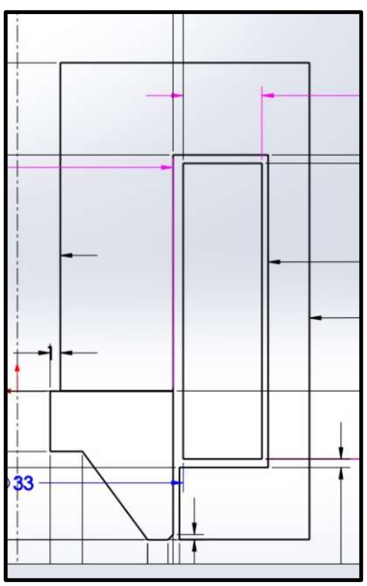

Figure 1: Example 2D cross-section of an armature/coil/backiron configuration

Step 3: Magnetic Finite Element Analysis

Magnetic finite-element analysis (FEA) is used to calculate the magnetic characteristics of a given actuator configuration. For axisymmetric actuators, a 2-D simulation is the most computationally efficient and results are typically very close to the actual 3-D geometry which may not be perfectly axisymmetric. The main outputs used from the magnetic FEA are force exerted on the armature and inductance of the coil, both of which are used in the dynamic simulations. Both values vary as a function of the coil current and the gap between the armature and actuator, so the outputs are 2-dimensional maps. Therefore, every actuator configuration requires on the order of 100 magnetic FEA simulations.

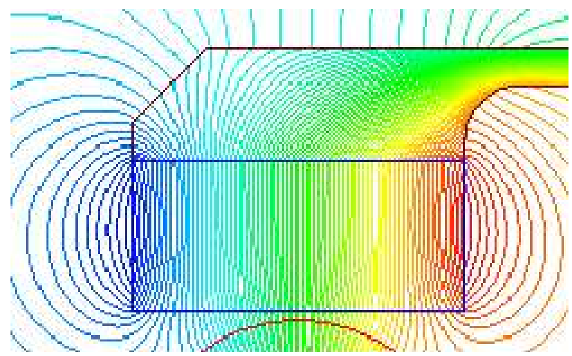

Figure 2: Example output from magnetic FEA showing flux lines

Some actuator metrics and down-selection can be determined from this step alone. For example, there may be a force/current constraint (i.e. a minimum required force with a maximum current limit), and some actuators could be deemed non-viable after producing the magnetic maps via FEA. The magnetics characteristics could also be used to make decisions to choose between base designs. For example, in Czero's recent project, iterations were run with two actuator options: one with a single force-producing gap, and the other with two. Reviewing the results of force vs gap over a range of configurations for each revealed that in general the two-force-producing-gap base design resulted in higher forces at larger gaps (in exchange for lower force at very small gaps), which were deemed advantageous for the application. This allowed for a down-selection of options before proceeding to the next step. Looking at the results of many runs throughout the design space for each option enabled this conclusion to be drawn, whereas evaluating just one or two geometries within each option would have been inconclusive.

Czero uses FEMM (Finite Element Method Magnetics) software for this automated optimization process, which has the advantage of a built-in scripting interface so it can be run from MATLAB. Final checks of magnetic characteristics can be run using a 3D magnetic FEA software.

Step 4: System dynamic Simulation

A 1-D dynamic model of the valve & actuator system is used to evaluate the performance of the system as a whole, with the magnetic properties provided from the magnetic FEA. The dynamic model of a valve-actuator system typically involves bodies for the multiple moving parts in the system (i.e. valve, armature, any other connecting pieces), springs, impact dynamics between the moving parts and the hardstops, friction, and the magnetic force generated by the coil. A sub-model of the coil is used to simulate the coil current in response to a command signal. The dynamic model may be initialized and controlled in several ways to evaluate different system performance metrics. The control scheme can also employ optimization routines. For example, to evaluate fast travel time while minimizing power, the dynamic model can be used with an optimization routine to find the minimum current required to achieve the target travel time with the model configured to actuate the valve once from closed to open. As another example, the coil sub-model could be employed by itself to evaluate performance metrics such as rate of current rise or dissipation with the valve in a fixed position, or dynamically with the valve moving. Czero uses MATLAB/Simulink for 1-D dynamic simulation.

Step 5: Process Results & Analyze

Once the performance metrics for all the configurations have been evaluated and compiled, these results are analyzed and organized using data visualization techniques to understand basic trends and which part of the design space is showing the best results. For example, Figure 3 below provides information about the performance of 500 cases in a single graphic (125 actuators evaluated for 4 valve strokes). Cases that were not able to actuate the valve in the required time at all are colored red, cases that were able to meet the time requirement but not the energy requirement are colored orange, and cases that met both criteria are colored green. This grid visual shows quickly how the change in stroke affects the range of options for meeting the requirements, and the strong effect of pole diameter, with more minor effects of wire gauge and coil aspect ratio.

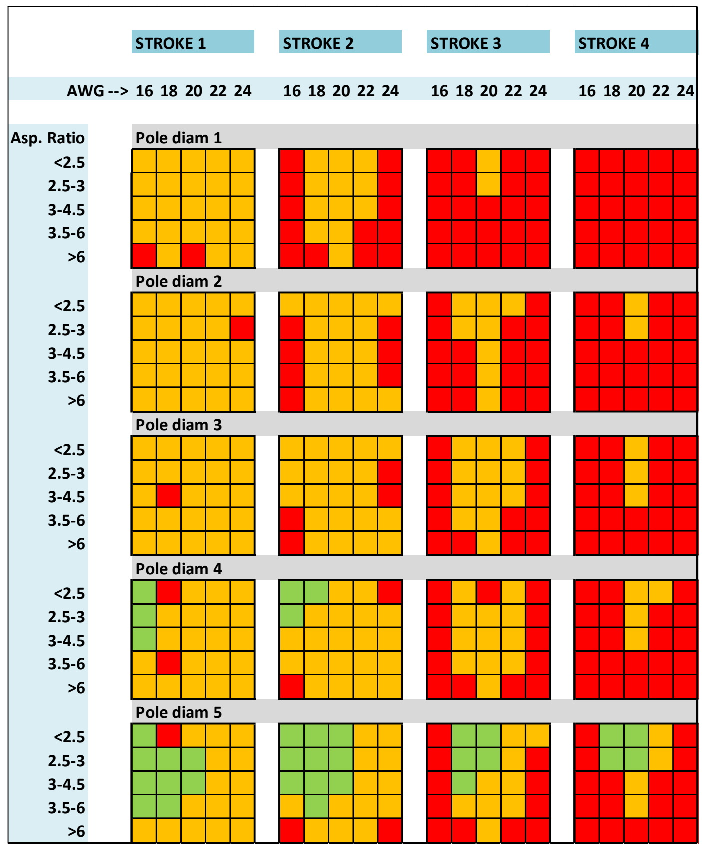

Figure 3: Sample data visualization showing the effect of 4 variables on a metric of interest

Often, this step leads to additional sets of runs as the design space is refined based on the results, new ideas are generated based on gained insights, or performance requirements are adjusted. After sufficient iterations have been completed, a final optimized actuator can be selected.

Conclusion

This paper described the automated optimization process of electromagnetic actuator design developed by Czero to search the design space quickly and efficiently for the best performing options. By investing the time in analysis up front to arrive at an optimized design, the overall R&D cycle can be significantly shorter, as each prototype is closer to meeting the desired outcome.

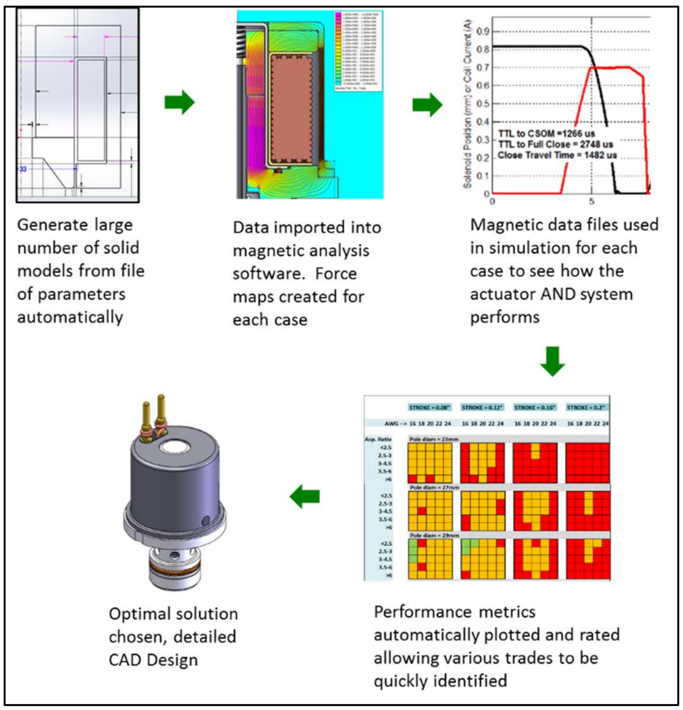

Figure 4: Overview of Czero's electromagnetic actuator design process

How Czero Can Help You

Czero's focus is on helping innovative companies solve the toughest engineering problems through deep expertise, creative thinking, and sophisticated analysis tools. Among many other capabilities, Czero can apply the actuator optimization process described in this white paper either directly to existing products, or to blank-sheet applications. This work can be performed as either an independent analysis task, or as part of a larger R&D project led by Czero.

Company Profile

Czero develops innovations for the automotive, defense, oil and gas, renewable energy, and clean technology industries.

Our award-winning engineers have 25+ years of experience working with innovation labs, startups, government agencies, and large OEMs in North America, Europe, Asia, and Australia.

Concept-to-prototype engineering R&D

Specializing in early-stage research and product development, Czero helps companies solve tough challenges and transform concepts into robust, tested prototypes of new technologies.

Services

- Mechanical design & solid modeling
- Dynamic modeling & simulation
- Finite element analysis (FEA) & computational fluid dynamics (CFD)
- Embedded controls
- Prototyping and testing
- Program & project management

R&D Specialties

- Advanced machine design
- Mechanical, electromechanical and electrohydraulic systems
- Energy conversion, efficiency and recovery
- High-bandwidth hydraulics
- Automotive powertrains
- Heavy-duty trucks
- Fuel systems
- Valve systems
- Hybrid vehicles