Multiphysics Analysis Electromagnetic Actuators (Solenoids)

ABSTRACT

Electromagnetic actuators, or solenoids, are devices that operate by producing magnetic fields to move an armature a desired distance at a desired force. They are used in applications such as fuel injectors, power distribution (interrupters, breakers, etc.), and various automotive, hydraulic and industrial applications.

PRODUCTS USED, VERSION

Maxwell® 14.0, Simplorer® 9.0, ANSYS® Workbench™ (ANSYS® Mechanical™, ANSYS® CFD™)

KEYWORDS

Actuator, solenoid, magnetic diffusion, system simulation, cosimulation, equivalent circuit extraction, thermal modeling

CONSTRUCTION DESCRIPTION

Typical electromagnetic actuators consist of a multi-turn coil that is configured around a ferrous pole piece and a moveable armature. Additional ferrous parts, such as a frame, provide a return path for the magnetic flux as shown in Figure1. When the actuator is connected to a voltage source, current flows through the coil turns, magnetic flux, is created in the device, and a resulting magnetic force is produced to move the armature from open to closed position. Other actuator configurations may include permanent magnets to assist in flux production or to help hold the armature in place while voltage is switched off in the coil. Voice coil actuators use permanent magnets to produce a magnetic flux that impinges the coil current and thus produces a Lorentz force on the coil. These devices may be 2-D or 3-D in nature and can include rotational motion or noncylindrical rotation (rocker motion).

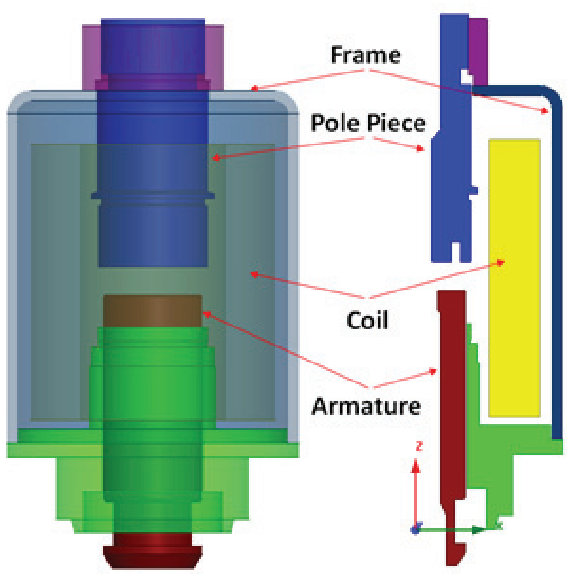

Figure 1: 3-D and axis-symmetric view of typical electromagnetic actuator, with frame, pole piece, coil and armature defined

The ferrous material of the armature, pole piece and frame are modeled with nonlinear BH curves to capture important saturation effects in these devices that can limit performance. Designing the size and shape of the armature and mating pole piece impacts the force profile on the armature and/or the closing time. Additionally, the design of the coil determines the electrical resistance and strongly impacts the inductance of the coil, since the inductance is equal to the square of the number of coil turns multiplied by the total magnetic reluctance of the nonlinear ferrous objects and air gaps. The ratio of the resistance divided by the inductance (L/R) is the electrical time constant; it determines how fast current can rise in the coil. Considering this rise time of the current due to the electrical time constant, the magnetic diffusion time (how fast the magnetic flux builds up in the device due to eddy currents) can also impact actuator performance. Shown in Figure 2 is the magnetic flux density from a voltage-sourced transient analysis. During the fast rise in current, the magnetic flux is crowded near the inner surface of the actuator before diffusing through the device, thus delaying the buildup of force on the armature. Similarly, magnetic effusion occurs when the voltage is switched off and the magnetic flux dissipates out of the device, which can delay the opening of armature.

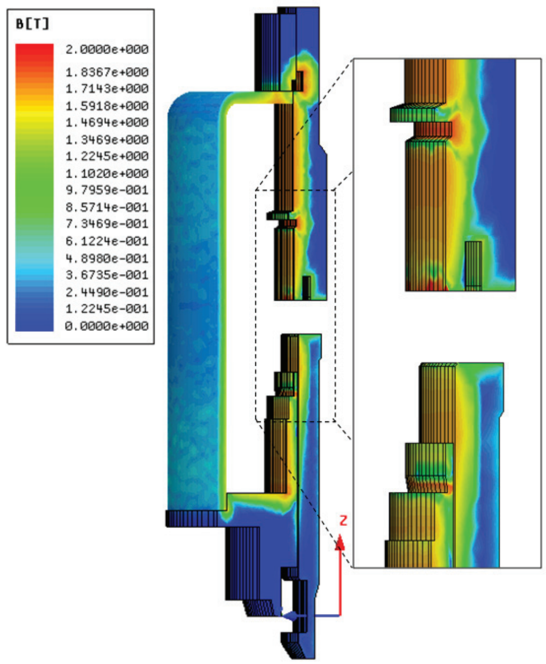

Figure 2: Magnetic flux density shown during a transient simulation after 0.001 seconds. Inset shows detail of the magnetic diffusion due to eddy currents. As time progresses, the fields diffuse through the thickness of the device, force increases, and the armature closes once the magnetic force overcomes spring and load forces.

STATIC AND TRANSIENT SIMULATION

Two-D and 3-D magnetic analysis can be performed using the Maxwell static or transient solvers. Often, the coil design (shape factor, number of turns and wire size) and geometry optimization can be done in a series of static simulations in which the current and position are varied to produce a family of curves representing armature force versus position and current. Since Maxwell uses automatic adaptive meshing for each of these variations, it is very easy to perform parametric sweeps or optimizations on these variables.

Beyond the static simulation approach, full electrical and mechanical transients can be considered to determine how fast the armature reaches the closed position using the Maxwell transient solver. Here, a robust simulation can be completed using an arbitrarily defined voltage source (or attached circuit using the Maxwell circuit editor), nonlinear materials, and mechanical equations of motion (including damping and load forces, which can be functions of position, speed, or time), in which eddy currents and magnetic diffusion are considered, as seen in the results of Figure 3.

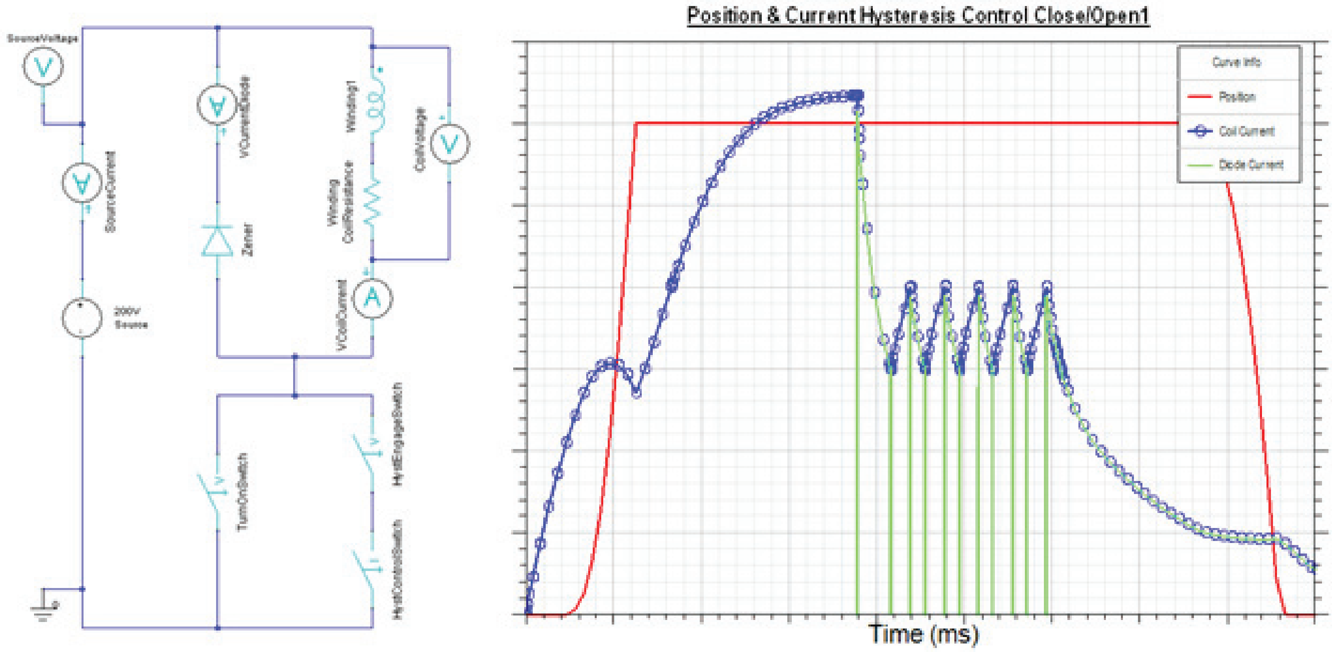

Figure 3: Using the circuit editor within Maxwell, a transient simulation with a chopped current controller is realized, showing transient waveforms of position, coil current and diode current.

SYSTEM SIMULATION

Simplorer is a multi-domain circuit and system simulation tool that models circuits, block diagrams, state machines and VHDL-AMS; it also dynamically couples to several other simulation tools from ANSYS. If a more-detailed electronic circuit is required, then Simplorer may be used either to cosimulate with Maxwell (in which nonlinear materials, eddy currents and magnetic diffusion is considered) or to use an equivalent circuit generated from a parametric sweep of position and coil current (in which eddy effects are ignored). Detailed semiconductor models and closed-loop control systems can be used with a detailed 2-D or 3-D actuator model that can be connected to a mechanical/hydraulic load using the available multi-domain components in Simplorer (Figure 4).

THERMAL-STRESS SIMULATION

Once the time domain coil and core losses are found in the electromagnetic models, they can be mapped to ANSYS Mechanical or ANSYS CFD (computational fluid dynamics) for thermal analysis within the ANSYS Workbench environment, as shown in Figure 5. The time-averaged losses are spatially mapped to the thermal models, where heat transfer coefficients are assigned, or are solved explicitly using ANSYS CFD. The steady-state temperature of the actuator is evaluated along with transient thermal performance and thermal cycling.

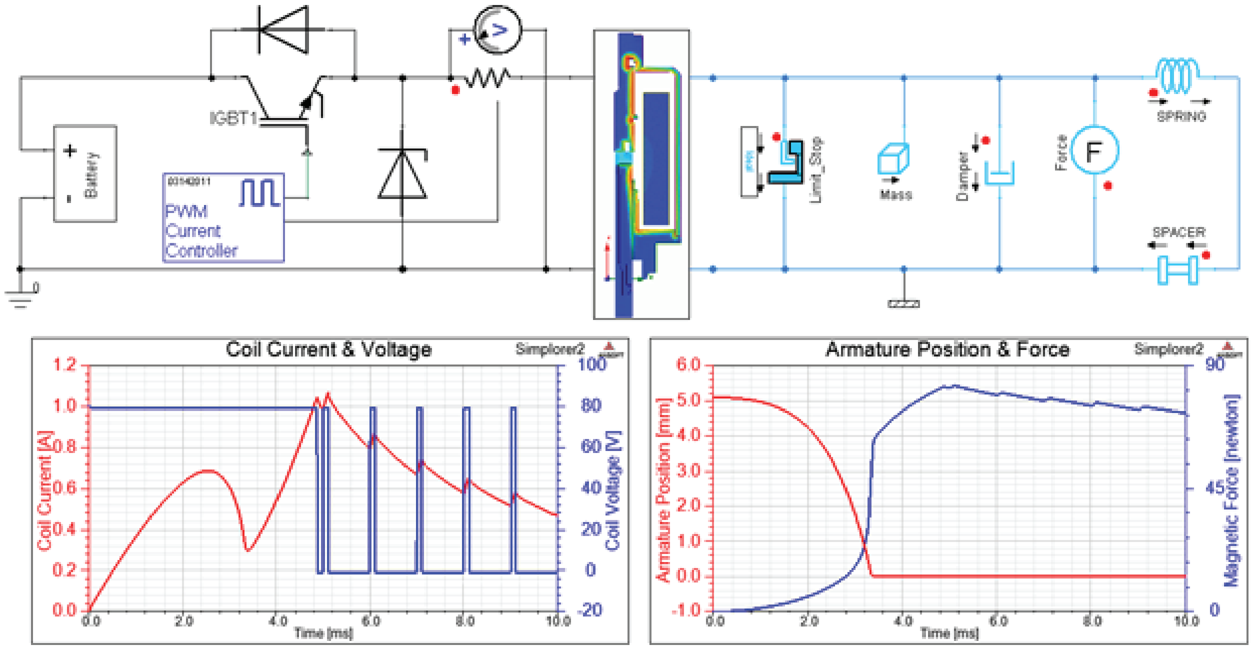

Figure 4: Robust system simulation in Simplorer showing a drive circuit coupled to the Maxwell FEA model through coupled transient link. Mechanical pins are connected to define mass, forces, springs and limit stops. Plots show coil current and voltage along with armature position and force versus time.

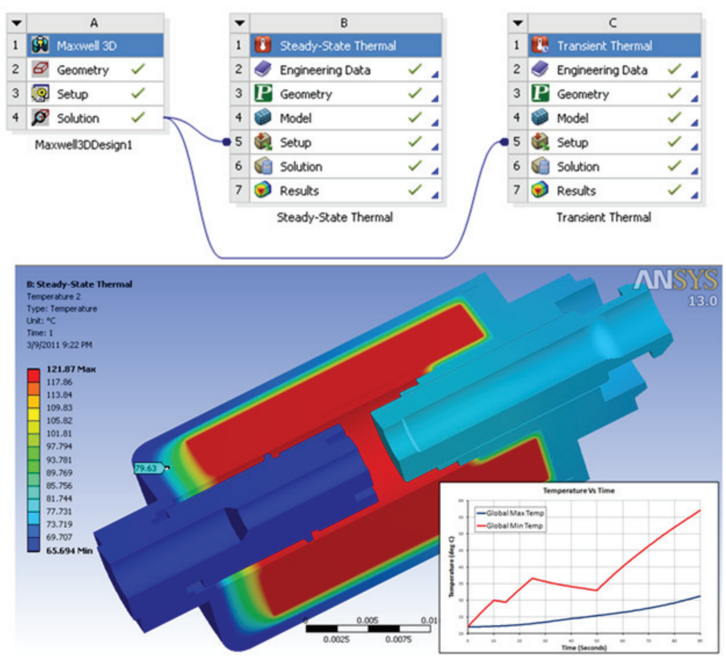

Figure 5: ANSYS Workbench enables mapping the losses from a magnetic simulation to a static and/or transient thermal simulation.

CLOSING SUMMARY

ANSYS provides a comprehensive analysis approach for electromagnetic actuators. Whether the application is static, transient, thermal or system analysis, there is an integrated tool set available to cover any level of analysis.

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