White Paper

Simulating Solenoid Valves

Abstract

The ability to accurately simulate power consumption of a satellite and its systems can be invaluable to a satellite system integrator. This paper describes a load to simulate a solenoid valve's power consumption with passive electrical parts. This simulation load can help a satellite system integrator understand the power requirements needed to actuate the solenoid valve without the need for the physical valve. The proposed solution in this paper uses an inductor and a resistor in series to match the inductance and the resistance of the solenoid valve.

Introduction

A major risk of satellite system integration is the power consumption of any subsystem going into the satellite. Giving the system integrator an accurate engineering model early in the integration process helps mitigate and eliminate any issues that arise. One key way that Benchmark Space Systems supports system integrators is by offering integration/evaluation kits (IEK) as shown in Figure 1.

In the case of Benchmark Space Systems' unique chemical propulsion products, the solenoid valves draw most of the power over the operational life of the system. The IEK models the power consumption and the functionality of the system by using the simulation loads in place of physical valves and sensors, making the IEK a fraction of the cost of an assembled system and with short lead times.

The power consumption of a solenoid valve in operation has several unique properties, and providing a high-quality model allows satellite integrators to deliver "on-time, first-time" to their customers.

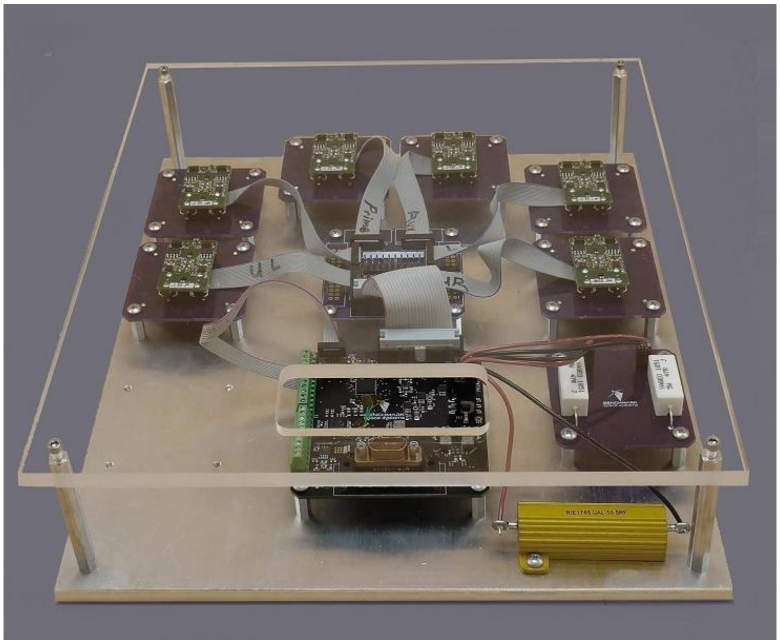

Figure 1: IEK built by Benchmark Space Systems

Construction and Operation of a Solenoid Valve

An electromechanical solenoid is a combination of an electromagnetic system and a mechanical system. A solenoid is an electromagnetically inductive coil wound around a moveable armature [1]. The coil is shaped in a way that enables the armature to move in and out of its center [2]. The plunger provides the mechanical force necessary to activate the control mechanism, for example the opening and closing of a valve.

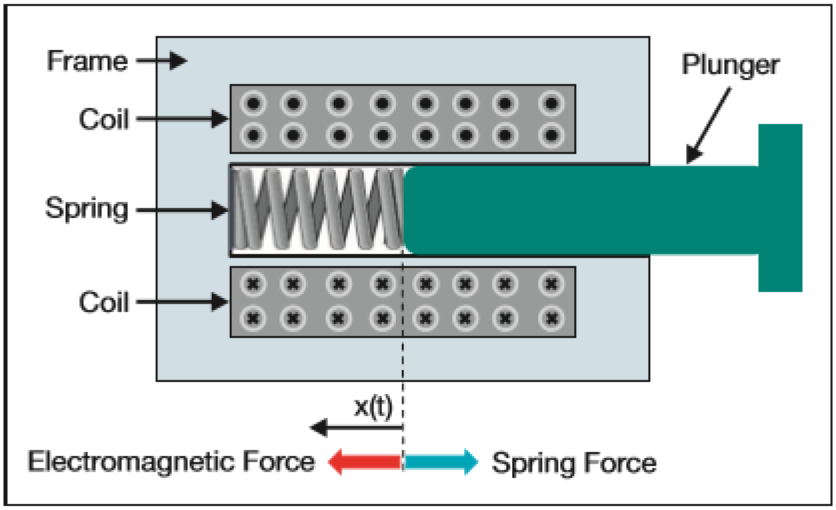

Figure 1: Cross sectional view of an electrometrical solenoid [1]

A valve can be constructed around the plunger and coil, as shown in Figure 2. The valve is operated by applying a large excitation voltage to the electrical pins. This excitation voltage increases the current in the windings, which produces magnetic field. The magnetic field exerts an attractive force on the plunger which pulls the plunger into the center of the coil.

Once the plunger has moved into the center of the coil, the magnetic field required to hold the plunger in place is less than the magnetic field required to move the plunger. Because of the reduced power demand to hold the coil in place, both the current within the coil, and the voltage can be reduced from that required to move the coil, and thus conserve energy. If the voltage and current were not reduced, the extra power would be converted to heat and could cause permanent damage to the valve.

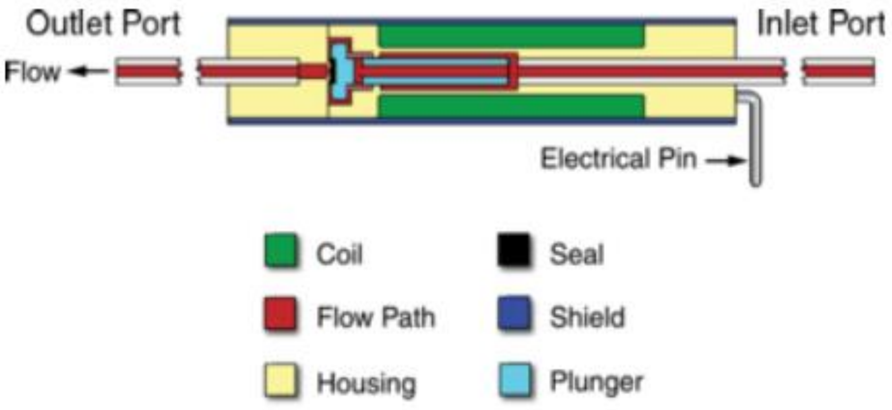

Figure 2: Cross-section of a valve [3]

. A solenoid valve can be represented as an inductor and a resistor in series, as shown in Figure 3. The inductance originates from wrapping the wire into coils around the cylinder. The resistance is a material property of the wire. As the plunger moves into the coil the inductance of the solenoid changes. The current and voltage measurements are a more relevant metric of the power consumption than the specific inductance valve of the solenoid

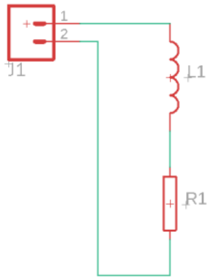

Figure 3: Electrical representation of a solenoid valve

Characterization of solenoid valve and simulation load

To determine if the simulation load is a good representation of the valve, both are characterized with the same driving circuit. The driving circuit consists of a power supply, a low side MOSFET which acts as a switch, an anti-parallel diode, and a control signal from a microcontroller, as shown in Figure 4. The system is driven with a +12-volt (V) source. A voltage probe is attached between the solenoid/simulation load switched terminal and ground, and a current probe is attached between the voltage source and the solenoid/simulation load. The valve is opened by a 12V spike for 2 ms in order to pull the plunger into the coil. The hold current is produced by Pulse Width Modulation (PWM) of the MOSFET at 20 kHz with a 13.5% duty cycle. The PWM operation causes the average voltage applied to the solenoid to be 13.5% of the supply voltage.

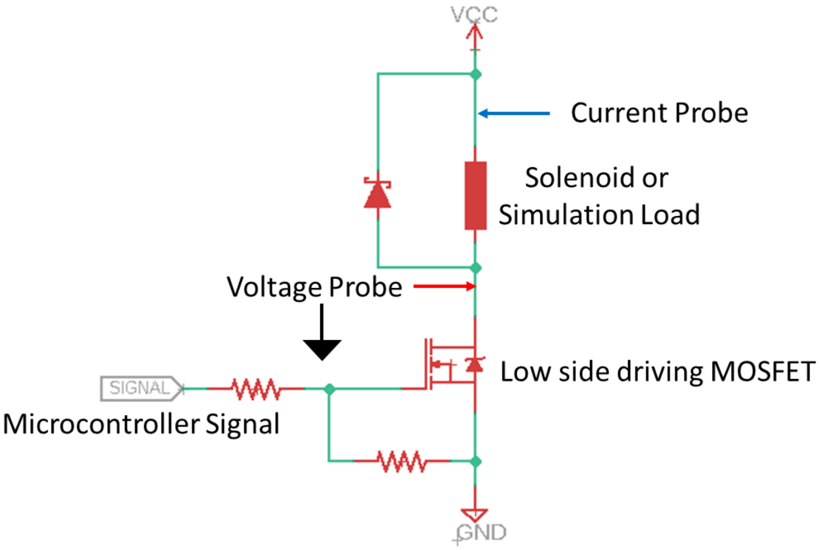

Figure 4: Experimental Setup

To ensure that the simulated load is an adequate representation of the physical solenoid valve, both the voltage and current waveforms must be as similar as possible. Figure 5 shows the measured voltage and current waveforms of the solenoid valve.

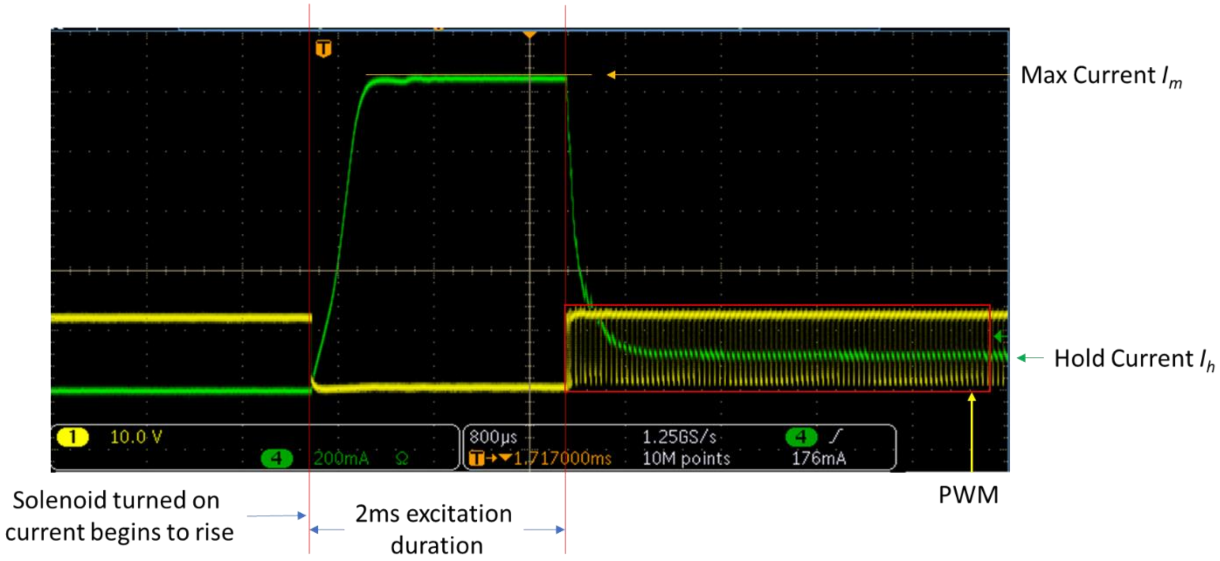

Figure 5: Voltage and Current Waveforms of solenoid valve

The green waveform is the measured current entering the valve from the source. The voltage across the MOSFET is the yellow waveform (the solenoid voltage is 12V minus this waveform). The time it takes for the current to reach its maximum, once the valve is turned on, is directly related to the inductance and the resistance of the solenoid, as shown:

$$v = L\left(\frac{di}{dt}\right) + iR$$

This equation shows the that voltage, v, is equal to the inductance, L, multiplied by the change of current over time, di/dt plus the resistance multiplied by the current. Therefore, the amount of time that it takes the current to reach the maximum current once the valve is turned on is a function both the resistance and the inductance of the solenoid valve. The time it takes for the solenoid to reach the maximum current of 1.048 Amperes (A) is 320 microseconds (µs).

Once the solenoid has reached its peak current, the inductance has no effect, and the current is a function of only the DC resistance. Observing the maximum current, the DC resistance of the solenoid valve is around 10.6 ohms.

After the 2 ms pulse, PWM operation begins. The current falls until it reaches the hold current of 120mA. The power required to hold the valve open is much lower than the power required to open the valve. In this case the instantaneous power drops from around 12W for 2ms to 250mW long-term.

Tuning the simulated load begins with finding the right DCR, then adjusting the inductance value to achieve the desired rise time. Choosing an off-the-shelf inductor is an iterative process since the inductance, DCR, saturation current, and slope of saturation all effect the waveform. The simulated load was constructed using two 6.8mH inductors in parallel and a 5Ω resistor in series to acheieve the best match with the solenoid valve current. Figure 6 shows the measured voltage and current of this simulated load. The yellow waveform is the MOSFET voltage and the gray waveform is the simulated load current. The current rise time for the simulated load is 335 µs and the maximum current is 1.1 A. The hold current is 120 mA.

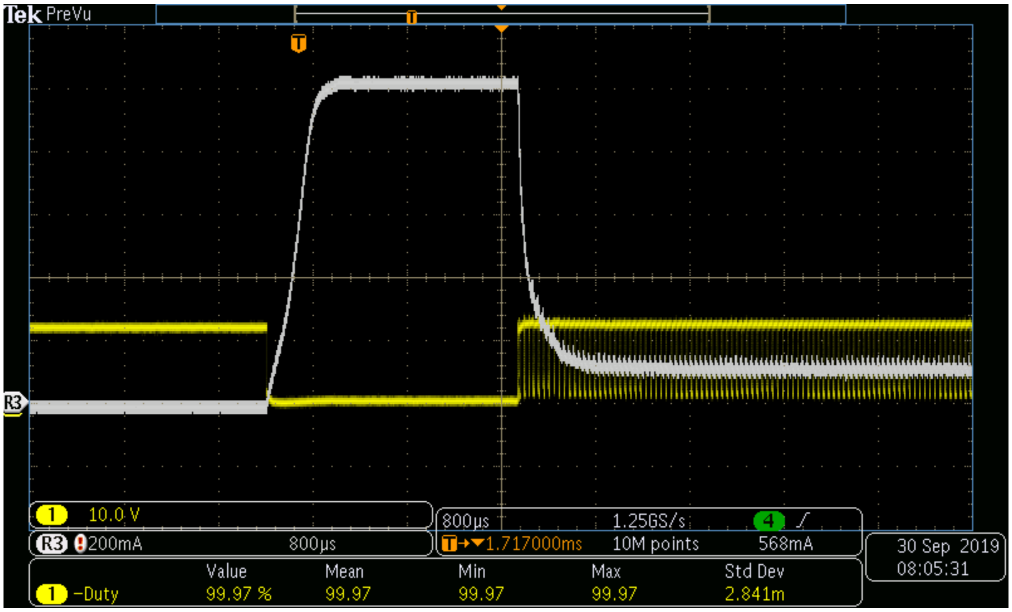

Figure 6: Simulated Load Wave forms

Table 1: Solenoid Valve vs Simulation Load

	Solenoid Valve	Simulation Load
DC Resistance	10.54 Ω	11.25 Ω
Max Current Draw	1.048 A	1.1 A
Hold Current	120 mA	120 mA
Power draw @ hold current	250 mW	250 mW
Current rise time	320 µs	335 µs

The comparison between the solenoid valve and the simulation load, in Table 1, shows that the two loads are similar. The power draw during the hold current is equal and the current rise time is nearly identical in both cases. Based on these values, the simulated load is an excellent analog for the solenoid valve with respect to both power consumption and spike-current rise.

Conclusion

The simulated load provides equivalent power consumption to the solenoid valve with simple COTS parts. The IEK provides system integrators with accurate behavior early in the satellite design cycle at a much lower cost than a complete system. Using accurate hardware early in the satellite design process helps integrators deliver "on-time, first-time" success to their customers.

References

[1] Manu Balakrishnan, Navaneeth Kumar N "Detection of Plunger Movement in DC Solenoids (SSIY001)", System Engineering & Marketing Industrial Systems-Motor Drive, 2015

[2] Texas Instruments, "Driving solenoid coils efficiently in switchgear applications (SLYT544)," Analog Applications Journal, Dec 2013.

[3] The Lee Company, 2020, IEP Series, <https://www.theleeco.com/products/electro-fluidic-systems/special-products/iep-series-solenoid-valves/iep-series/>