Musical Instrument Accessibility

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Introduction

Electromagnetism offers unique capabilities for the actuation of mechanical components such as switches, motors, and locks. A solenoid is an electromagnetic device comprised of a coil of tightly wound insulated wire around a hollow core. A captive ferromagnetc cylindrical piston, approximately as long or longer than the core, is suspended partially within. An electrical current passing through the coil generates a magnetic field which acts upon the piston, drawing it into the core. Electromagnets are constructed in much the same way, except the wire is wound around a fixed ferromagnetc core which itself becomes magnetized when electrical current is passed through the coil.

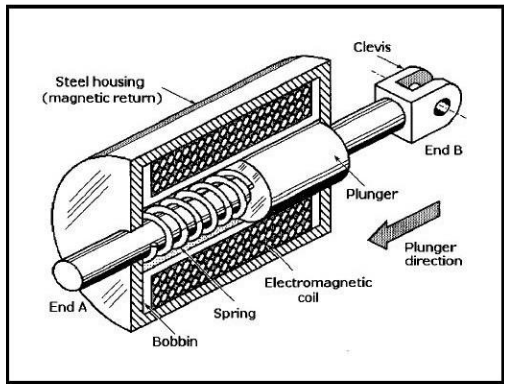

Figure 1. One of many typical solenoid configurations. When energized, End A and End B provide pushing and pulling action, respectively [3].

Electromagnet and Solenoid Physics

In a solenoid, the magnetic field generated by the an applied current, induces a magnetic field, causing an attractive force which draws the piston to the center of the coil. Though the field switches direction when the current is reversed, the effect on the solenoid piston is identical, unless the piston itself is a permanent magnet, or otherwise magnetized [1].

This behavior lends itself well to pulling action. To achieve pushing action, a plunger made of some non-magnetic material must be affixed to the end of the piston being drawn into the solenoid, such that it extends through the body of the device. Thus, when energized, the solenoid pulls at the piston end and pushes at the plunger end [2].

The greatest advantage that a solenoid has over other linear actuation methods, such as a servo motors is actuation speed. A solenoid may have a response time several orders of magnitude quicker than a servo.

Limitations of Electromagnetism

Electromagnets can maintain considerable holding force on an object; consider electronic door locks or scrapyard electromagnetic cranes. They are range-limited, however, in their ability to do work. A powerful electromagnet must nearly make contact to the target surface before it can "latch", after which it can provide enough holding force to lift several tons.

The magnetic field falls off rapidly beyond the length of an electromagnetic coil [4]. The size of an electromagnet with a strong enough field to act upon a small ferrous or magnetic mass just a short distance away and the power it would take to energize it make mechanical actuation by electromagnet an unfeasible solution for most applications.

Similarly, the force that an energized solenoid can maintain is greatest when the piston is drawn fully into the center of the coil. The force exerted on the extended piston as current is applied is relatively small. For this reason, most solenoids are rated for their *holding force*, not the pushing or pulling force. This poses a challenge to those wishing to use a solenoid for actuation of a mechanical device.

An obvious solution to this problem is to employ larger, more powerful solenoids, but this is costly in terms of power consumption, space, and price per unit. Another solution is to sacrifice some amount of stroke, the distance that the solenoid plunger extends when energized, for "running room". Positioning an unpowered push-type solenoid a short distance from a target device allows it to build up some momentum as it is energized, which may be useful in overcoming device inertia; similarly, a pull solenoid may be given slack.

In this way, one may be able to use lower-cost, more compact components to achieve the desired results; though every application is of course unique. It will be assumed from here on that this is the method of operation.

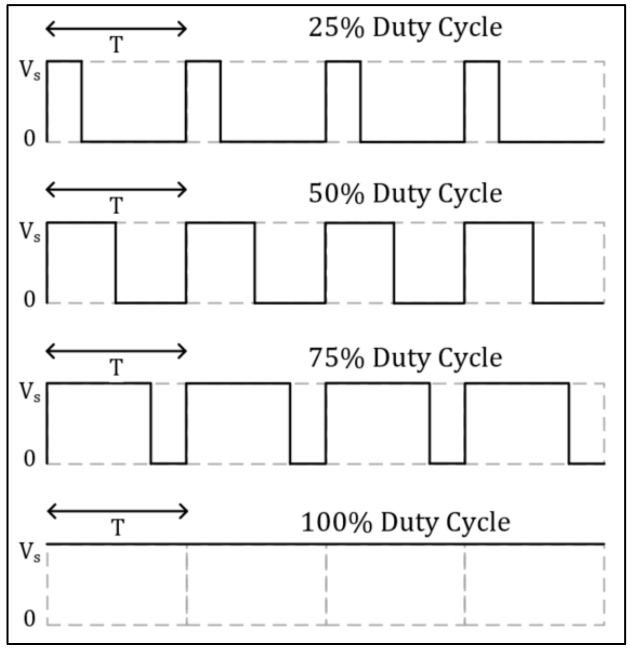

Figure 2. A digital voltage source can be implemented as a variable voltage source by switching it on and off rapidly, such that the average voltage seen at the terminal is a percent of the digital voltage level equal to the percent "on" time.

Solenoid Control

As stated above, a solenoid is operated by passing current through its windings. Passing more current results in a stronger internal magnetic field and a more rapid extension of the plunger. While most electronic components will come with a voltage and current rating from the manufacturer, for which to operate the device, it may be desirable for a given application that the target device be operated with varying force or speed. In such cases, it is therefore necessary to be able to vary the current through a solenoid. Pulse width modulation (PWM) is a simple means of achieving this.

Pulse Width Modulation

PWM is a means of varying the voltage delivered by a digital (constant level) source, by controlling the *on* time, or duty cycle of the source. Duty cycle, typically controlled by a microcontroller, indicates the percentage of a fixed period that the source remains on, supplying a highly controllable average voltage. The result is a rectangular waveform with a fixed period, where the width of the rectangular pulses varies according to duty cycle.

Voltage-Controlled Current Source

Most devices capable of PWM switching cannot supply sufficient current to drive a solenoid. It is therefore necessary to introduce a switching circuit capable of sustaining high current. Power transistors are ideally suited to this purpose, as they can deliver the required current required, and switch rapidly enough to be controlled using PWM. A Metal Oxide Field Effect Transistor (MOSFET) is preferable to a Bipolar Junction Transistor (BJT) in this case because the MOSFET has lower on-state resistance, therefore it dissipates less power and is a more robust design for power applications [5].

Using a logic-level MOSFET ensures that the switch operates only in the saturation (on) and cut-off (off) regions, never in the triode (resistive) region, when operated with a digital PWM controller. This allows FETs to be used in power applications (generally considered circuits that draw more than $1A$ of current), without heating up excessively to the point of failure. Power FETs can pass currents more than $100A$ [6].

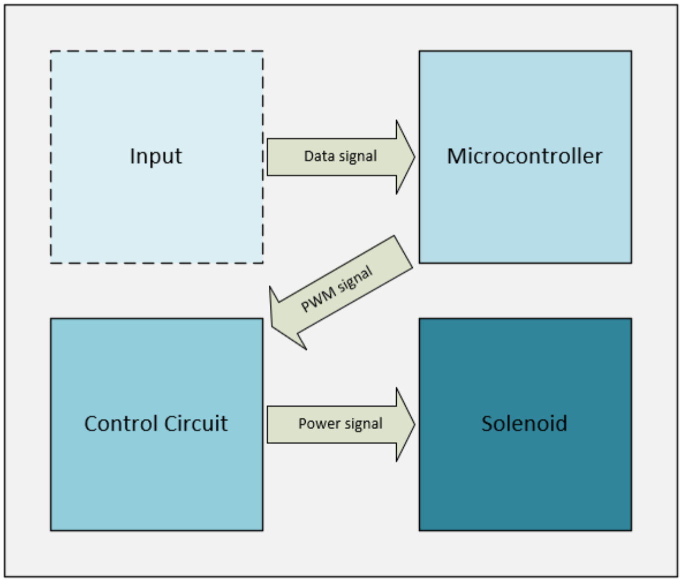

Figure 3: Block diagram of a solenoid driver

Further Consideration

PWM Noise Mitigation

It should be noted that driving any inductor, be it solenoid, electromagnet or inductive motor, using PWM may result in audible noise which may be undesirable depending on the application. This generally results from the PWM switching frequency being within the range of human hearing, which is default case for many PWM controllers. To resolve this, the microcontroller timer governing the PWM switching frequency may be adjusted out of ordinary human hearing range.

Mechanical Solenoid Noise

Again, depending on the application, solenoids can be undesirably loud when snapping open and closed under normal operation. If they are to be operated in an environment where people are present, it may be necessary to employ sound dampening techniques. This is situation-dependent and could be as simple as installing foam washers on the plunger or designing a sound absorbing enclosure to house the mechanism.

Multi-Solenoid Control

In most cases, it will require more than a single solenoid to accomplish the design challenge at hand. Most hobby-level microcontrollers have a limited number of PWM ports available. To design a more sophisticated system, it will be required to design a control circuit using multiplexors or shift registers. Additionally, multi-port PWM controller shields are commercially available and can be easily integrated with most microcontroller platforms. Fig. 4 shows an array of solenoids controlled driven by two control circuits and a single microcontroller to strike the keys of an acoustic piano.

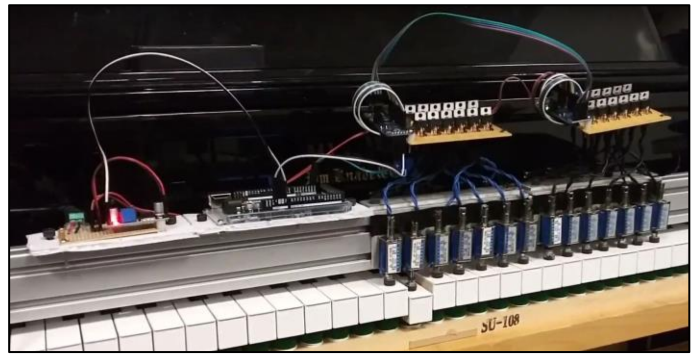

Figure 4. Solenoids playing an acoustic piano

References

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