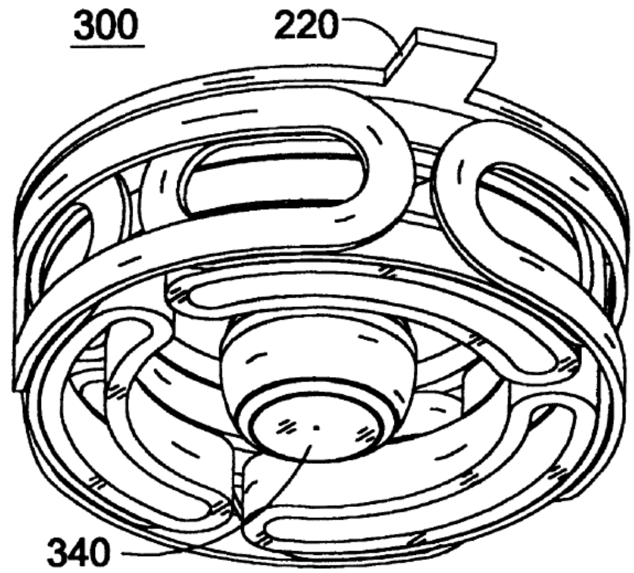
A Brief History of Magnesense Valve Solenoid Technology

by Joseph Seale

1986-99: Medical Device Applications

In 1986 we started aiming ultrasound beams with a two-axis tilt mechanism. By the mid-90s we were using magnetic levitation to move and tilt an ultrasound transducer (3-axis translation, 2-axis tilt) for peeping through little soft spots in the human cranium and lining up on blood vessels to measure bloodflow (U.S. patents 5,884,140 and 6,131,459).

U.S. 6,131,459

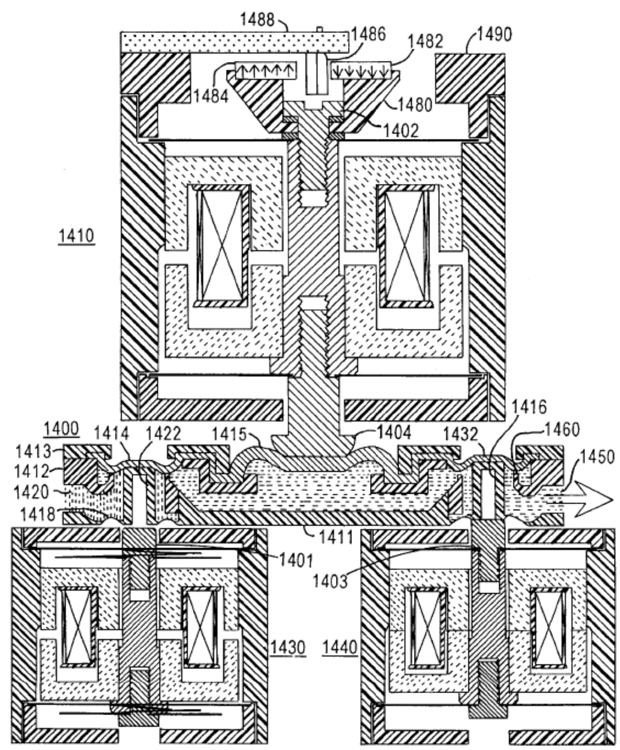


A solenoid for a medical infusion pump is shown in the patent figure on the right (from U.S. 6,208,497). We used ferrite pot cores as solenoids to open and close inlet and outlet valves (on the lower left and right) and a larger pot core pair to pull a spring loaded plunger (center top) operating on a fluid diaphragm.

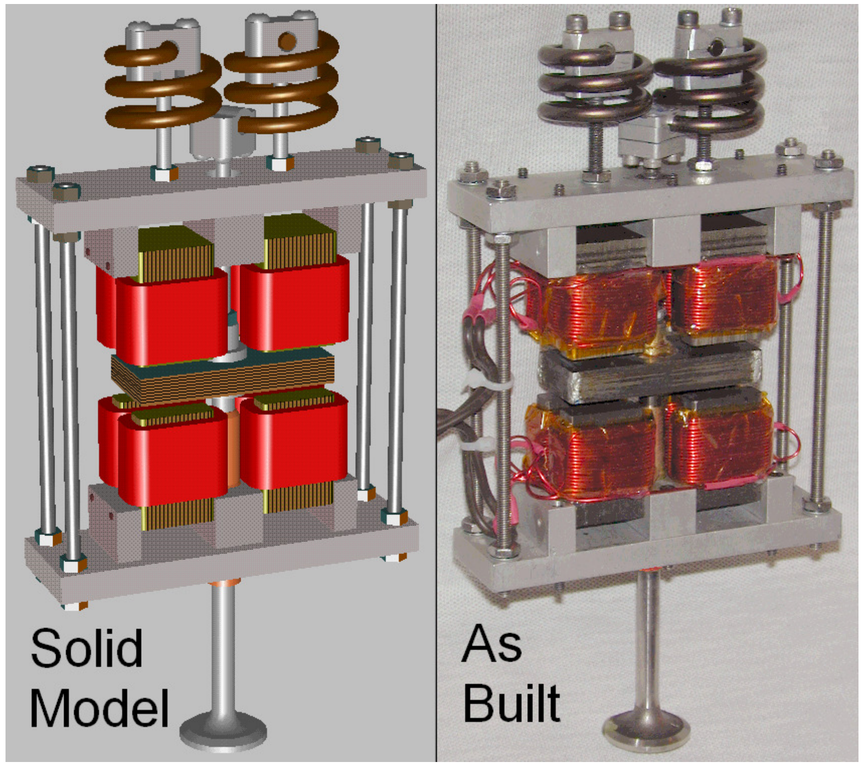
We learned how to soft-land these solenoids, first with analog circuitry, then a microprocessor. They had to be quiet enough to operate by a bedside at night. These solenoids were much easier to control than automotive valve solenoids, which made them a good education for us:

- they didn't have to move fast;
- they were single sided (so their motion was not launched abruptly by a preloaded spring;
- they were made of ferrite, which doesn't handle the high flux densities needed for engine valves, but ferrite has much more "ideal" behavior than iron: very low hysteresis, high permeability, no eddy currents.
- they used both a Hall effect sensor and a flux detection coil to measure position

U.S. 6,208,497



2000-2001: Magnesense, Automotive Effort



Our first engine valve solenoid became a platform for trying out a new development: a spring that would fit the geometry of a cylinder valve solenoid. The approach with other solenoids, then and to this day, relies on two large opposing compression springs, one of them set into the engine block. Each of these springs is quite a bit larger than an ordinary valve return spring, as needed to achieve the high centering force required to move a valve quickly between its full-open and full-closed positions. We figured that if the valve return spring could go back to its original size while the remaining restoration force came from a compact push-pull spring fitting above the solenoid, then the cylinder head modifications could be reduced considerably. By designing a spring capable of both compression and tension, we could operate the metal almost symmetrically about a neutral stress, allowing for considerably more energy storage per unit of spring mass. We settled on side-by-side helices, joined across the middle, as a way to fit the flat rectangular envelope needed to stack valve actuators up side-by-side at the spacing needed in a multi-cylinder engine. We got Peterson Spring interested, and they agreed to bend some prototype springs for testing.

The big challenge was to capture the spring ends and middle in a way that would allow reversing push-pull forces without developing any slop and without chafing the spring metal at the clamp. We developed a clamp design in which a hard rubber sleeve would surround the spring wire and be clamped in high compression. Rubber gets torn apart by tension or an alternation of tension and compression, but our studies of elastomer dynamics (see Seale's U.S. Patent 6,631,647, *System and Method for Quantifying Material Properties*) indicated that if the rubber were kept in compression at all times, and if the force transferred from the clamp to the wire were transmitted mostly differences in positive pressure rather than by shear forces, then the rubber would last indefinitely.

The solid model image shown below (next page) and the adapted patent figure illustrate the concept. The curved lines (767) crossing the rubber sleeve (633) indicate how straight radial lines across the sleeve become distorted by shear forces when the large spring wire (410) in the middle is pushed down (force arrow 763). The moderate shear in the rubber gives rise to a large difference in pressure from top to bottom, opposing the large downward force of the wire almost entirely by high pressure below and a lower positive pressure above. The squeezing force of the clamp (arrows 751, 762, 764 and 765) assures that the rubber is

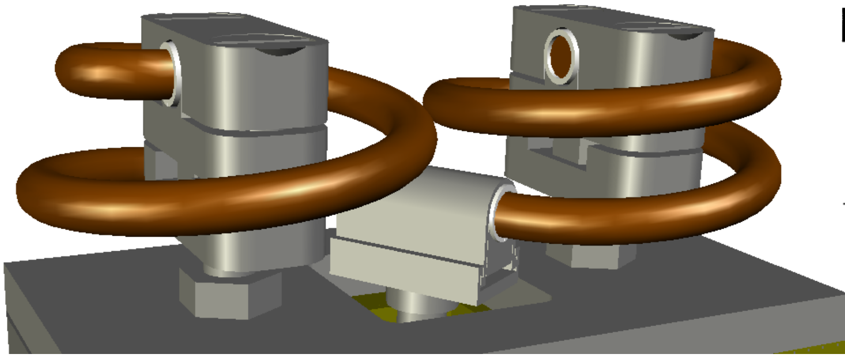
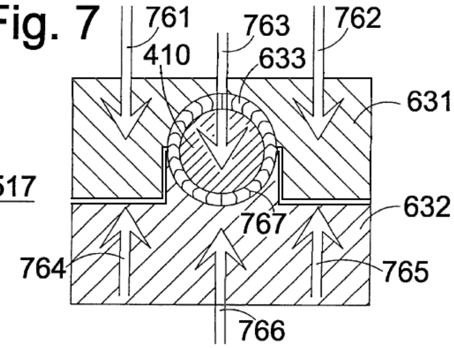


Fig. 7



always in compression, which it withstands without damage. The pressure tapers off to zero at the ends of the sleeve, where all the stresses are moderate. Half the patent specification and important allowed claims are devoted to the clamping method. The economy of this design is that the spring ends do not require grinding, as with compression springs. Thus, this compact spring is expected to fit in an available rectangular space, add less moving mass than opposing compression springs handling the same forces and motions, last indefinitely, and cost less, even counting the cost of the clamps.

Another design innovation tested in our prototype was the flat-lamination armature, illustrated schematically in the patent Figs. 3 and 4 below and evident upon examination of the “Solid Model” and “As Built” solenoid images of the previous page. Referring to the patent Fig. 3 (below, left), the optimum configuration for minimized eddy currents would use narrow vertically-stacked “I-core” laminations for armature 330, putting these laminations in the same plane as the “E-core” laminations above them. This stacking direction would lead to a very weak armature, easily broken along the cleavage boundaries of the laminations. Pinning or welding of vertically stacked laminations would open up eddy current conduction pathways, significantly reducing the advantage of having laminations. Industry practice with valve solenoids was to use a solid armature, accepting considerable eddy current losses. We recognized that the eddy losses for the horizontal stacking pattern of the Fig. 3 armature would be only slightly worse than for the fragile vertical stacking pattern while lending much greater strength. Patent claims to this effect were allowed, while actual operation of the “As Built” solenoid (previous page) confirmed our expectation of acceptable eddy current losses.

Fig. 3

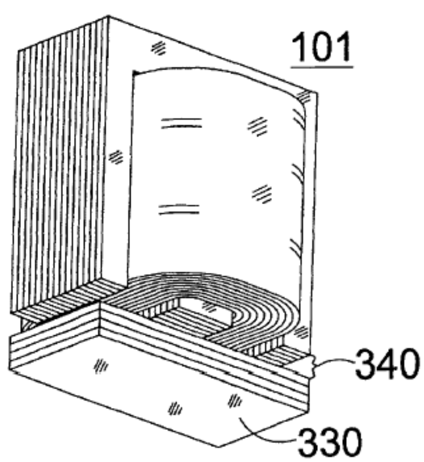
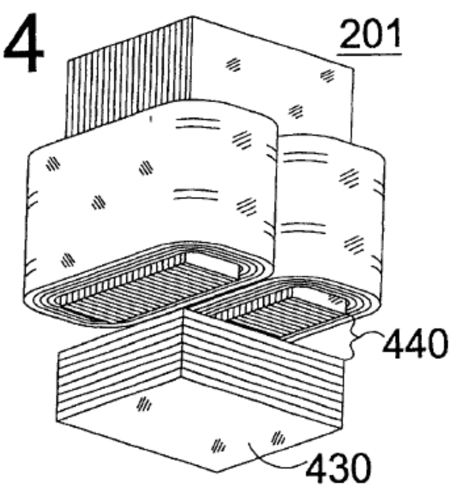
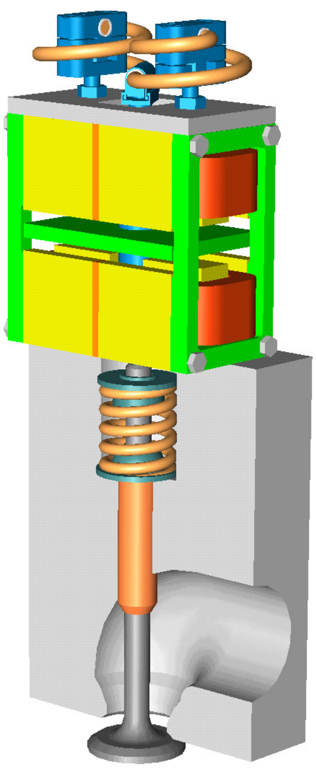


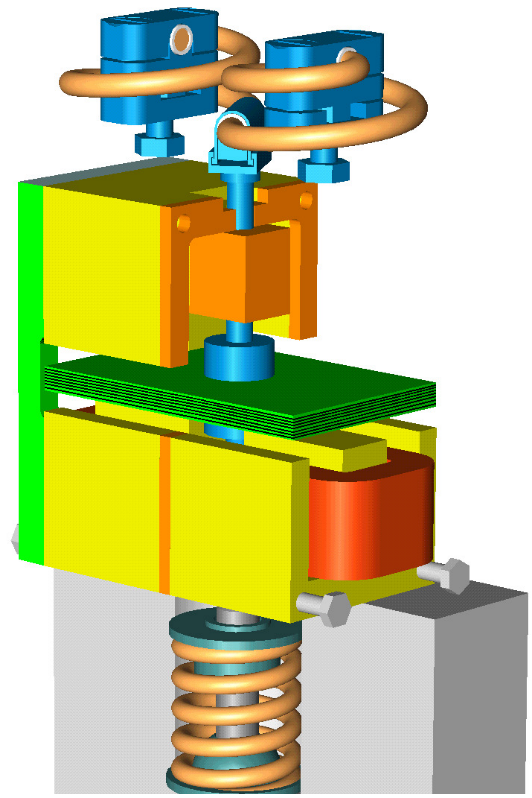
Fig. 4



Refined Automotive Valve Solenoid

Based on our experience with the experimental prototype, we designed a much more compact valve solenoid having lower moving mass, higher speed, and handling the same gas forces acting on the valve. The design again incorporated a flat-lamination armature, as visible in the right-hand illustration below), but this time with the thinner, lighter armature made possible by going to an E-core yoke: see the patent Fig. 3 above on the left, as contrasted with the U-core of Fig. 4 above on the right. The design is shown in a color-coded solid model below on the left and cut-away on the right. As revealed in the cut-away version, a winding (dark orange) goes through an E-core yoke (yellow). The center-tongues of the yoke laminations near the middle are cut away (as seen in the top yoke) and those center laminations are replaced entirely by a solid piece of bronze (light orange) which extends into a cube-shaped center bushing for the blue shaft. The valve (gray) is pushed up by a conventional valve spring and meets the bottom of the solenoid shaft (meeting point barely hidden) at a lash point where the solenoid shaft separates slightly from the valve shaft when the valve closes.





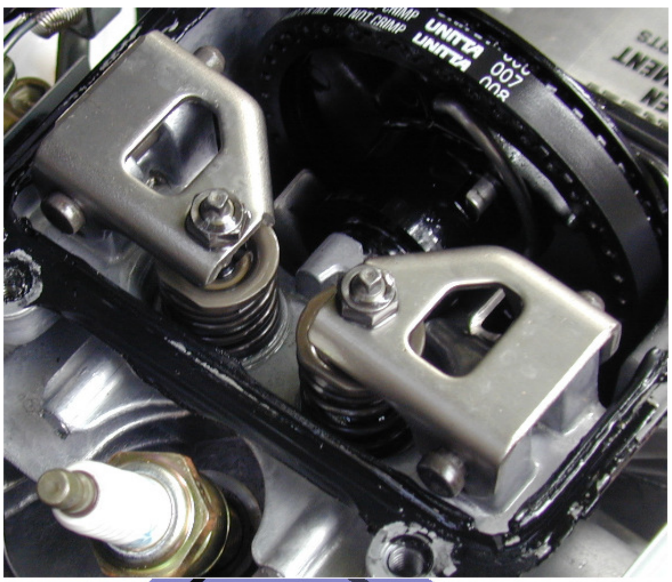
Re-Focus: Small Engine Cylinder Valves

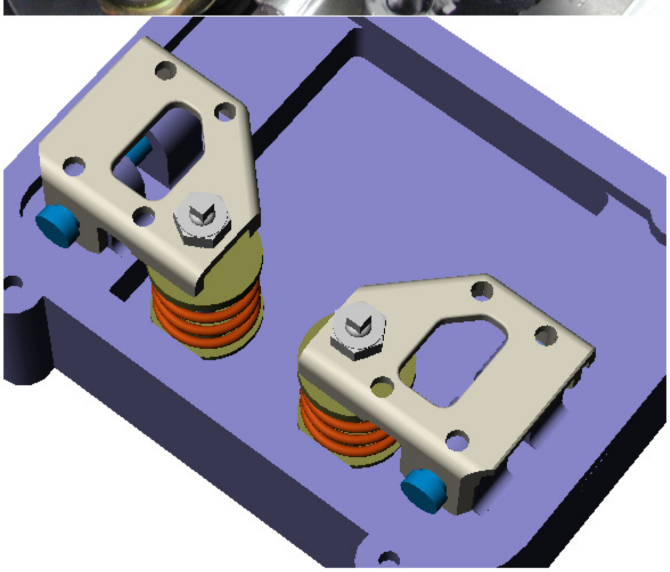
We were unable to arouse industry interest in the emerging Magnesense technology. A decision was made to re-focus our efforts on small engines. Engineering of a small-engine valve was expected to be considerably easier for several reasons:

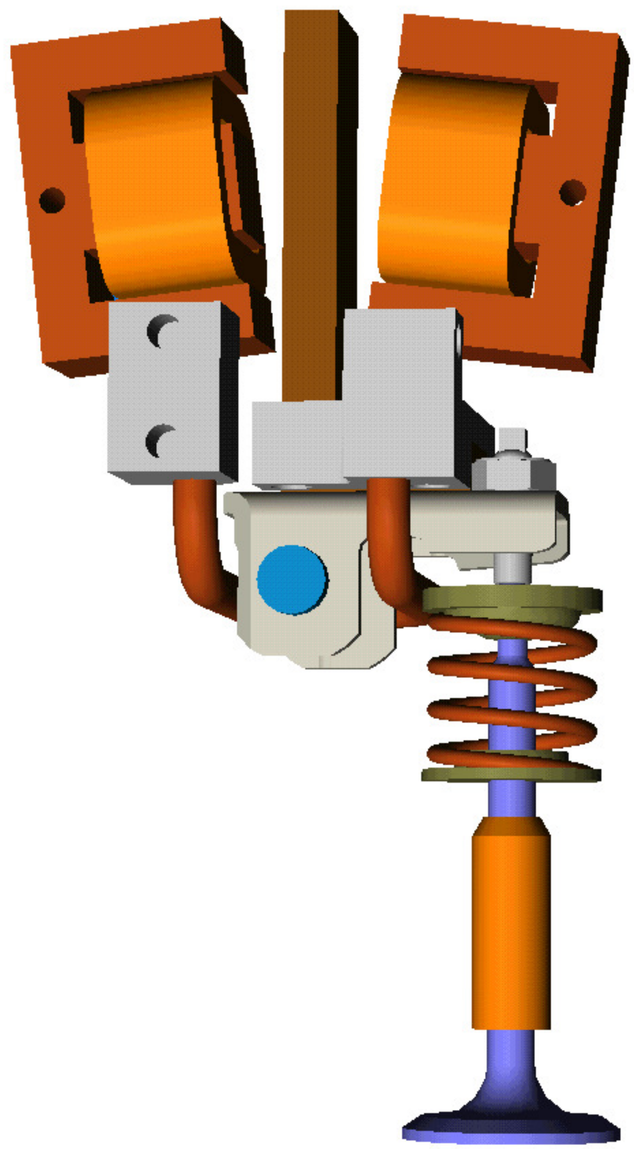
- A lower RPM requirement allowed a lower speed valve.
- The space constraints were not as severe.
- Service life did not have to be as long.

We would need to take maximum advantage of these simplifications, because the price would need to be much lower in the small engine setting. Whether or not a 42-volt standard might be on the way for cars, we would need to design for a 12-volt power supply in the small engine field. We would need to make do with a very inexpensive microprocessor or DSP. After a few false starts, we settled on the Motorola 56800 DSP family.

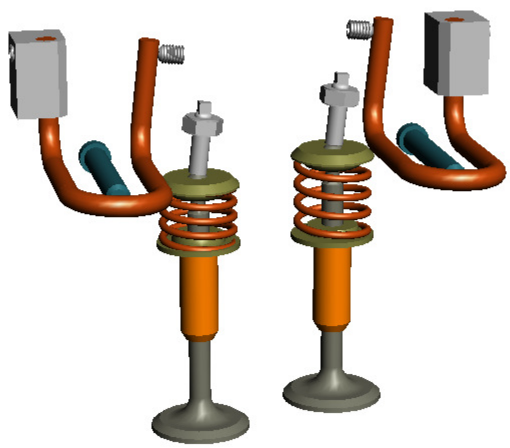
After examining the valve rockers in a Honda generator engine (below, left), we decided to depart from the traditional in-line solenoid structure and develop a magnetic rocker design that would functionally replace the cam-driven valve rockers seen below on the left. The result was the solenoid below on the right, using a vertical armature rocking between two e-core yokes. Note the solid model illustrated below the engine photo, showing holes drilled in the valve rockers for bolting on the clamp shown below on the right. This clamp holds down the bottom horizontal segment of the L-shaped rocker and also captures one end of a folded torsion spring. The rocker itself consists of L-shaped laminations, this time stacked in the same plane as the E-core yokes on either side.

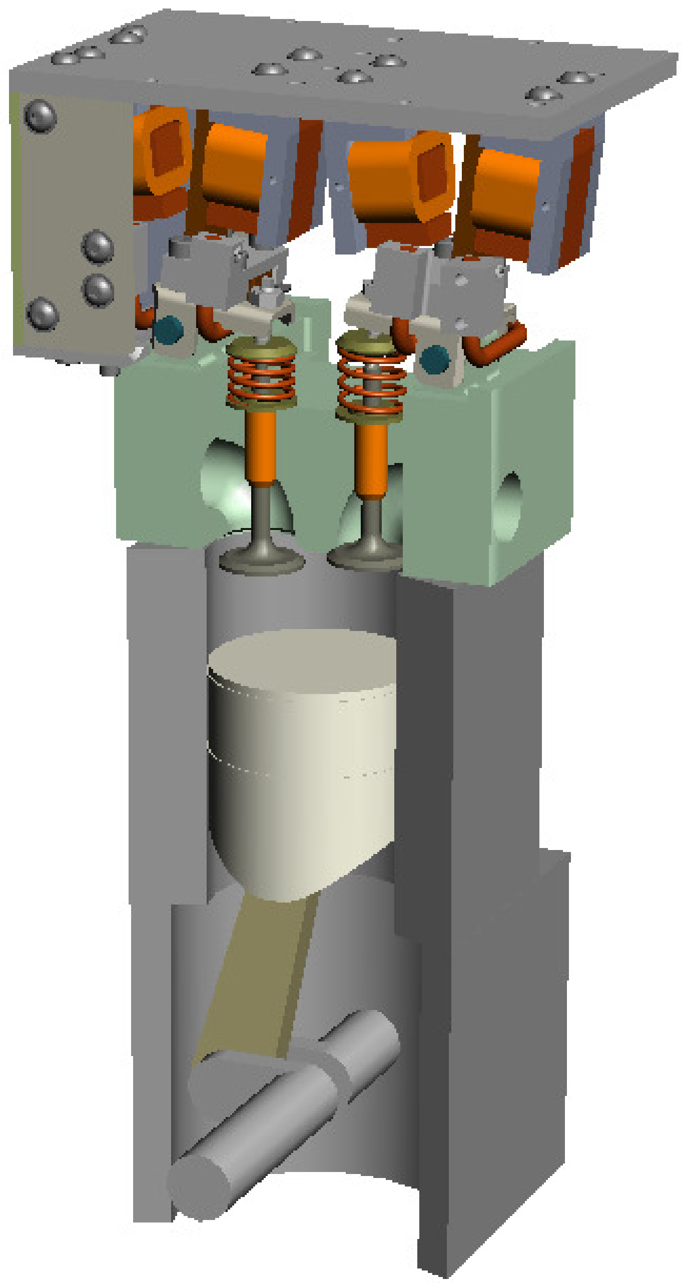






The valve rocker employs yet another non-standard spring design: a folded torsion spring making a U-shape in a horizontal plane with the ends of the "U" bent up. The same aluminum piece that clamps down the armature "L" also receives one of the upward-bent ends of the spring. The other end of that same spring is fixed, screwed down adjustably to the front surface of the valve and solenoid enclosure, where the recessed screw holes are seen facing the viewer in the image above on the right. The action of the torsion springs is seen in the view below on the left, with the rocking clamp and valve rocker removed, leaving only the rocker pivot pins and the set screws that hold the moving ends of the springs. The lash adjustment screws pressing down on the valve ends are threaded through the valve rockers, which are removed from view. The action of the torsion springs is readily seen.





The valves and actuators are seen in the context of the cylinder and piston on the right. A motion picture of the valves and piston head is provided in low and high bandwidths.

Now that we have the illustrated valve rocker design operating on an instrumented lab bench, we understand how to make it smaller easier to fabricate, and especially how to facilitate its assembly and alignment. Its power consumption is extremely low, and design tradeoffs could reduce the size while maintaining acceptably low power consumption.

Sensorless Measurement and Control Technology

Our recent work is summarized under four topic headings:
1. Theory and Modeling
2. Sensorless Position Measurement
3. State Space Control
4. DSP Control

1. Theory and Modeling

Our efforts in mechanical and electromagnetic design have been more than matched by our efforts in the area of sensorless control using an inexpensive Digital Signal Processor (DSP). In the area of theory, although solenoid theory can be understood from a combination of physics and engineering texts, Seale's paper "Basics" derives the specific results that are need for solenoid control algorithms. The approach in this paper emphasizes a key variable, flux linkage (symbolized variously as λ or $n\Phi$), commonly used in papers on rotary motors but less used in others' work on control of linear solenoid actuators. This paper assumes ideal linear magnetic properties throughout. The paper "B vs H Narrative" reviews an empirical exploration of non-ideal magnetic properties, defining the practical limits of the "Basics" paper. This second paper documents measured effects of saturation, hysteresis, and eddy currents in the yoke and armature design of our small engine valve rocker solenoid.

Results from both papers are incorporated into dynamic simulation models of the valve rocker illustrated on the previous page. Simulation efforts have proceeded in three stages:

- Simulate the complex dynamic behavior of a valve solenoid;
- Employ the solenoid simulation to develop a "trajectory map" for dynamic control;
- Simulate the performance of a control system using the "trajectory map" (see below)

2. Sensorless Position Measurement

Bergstrom's approach, as described and claimed in his patent "System for Control of an Electromagnetic Actuator," was part of the original motivation to found Magnesense. Again, our patent summaries section provides a good description, as reviewed briefly here. The crux of the invention is indirect measurement of armature position based on measurement of the solenoid winding current, occasional voltage measurements (e.g., to track the relatively slow fluctuations of the power supply voltage) and computations that determine the average inductive component of voltage driving the solenoid winding. The winding flux linkage is determined by time-integration of this inductive voltage, with drift corrections applied at various points where it is possible to compute absolute flux (e.g., when the winding current is zero or when the armature position can be inferred from various symmetries.) Armature position is computed at frequent short intervals along a trajectory, based on the changing ratio of current/flux-linkage. Magnetic force is implicit in the data defining position, velocity, and flux linkage. Thus, the system has robust information for control. No sensors are require in the actuator, and extra sensor wiring to the actuator is avoided.

Actual implementation of this method has proved quite time consuming, requiring good models and a thorough grasp of the entire electromagnetic process. Having mastered the subtleties of our own system and achieved excellent sensorless position measurements, we believe that the technique can be adapted to operate the actuators of other companies, simplifying them and reducing costs.

3. State Space Control

Our pending "State Space Control of Solenoids" patent, again described under patent summaries, incorporates the knowledge and experience of the previous two sections. There are two main features to this control approach:

- control of flux linkage as a function of position and velocity; and
- pre-defined trajectory information in the (position, velocity, flux-linkage) space, adapted to the specific characteristics of the solenoid to be controlled and defining, from any point in this state space, what the next controller output voltage should be.

The time integration of inductive voltage to yield flux linkage, and the closely related process of controlling flux linkage, come out of item #2, sensorless position measurement. The pre-defined trajectory information comes out of the simulations of item #1. This information effectively spans a band of state-space trajectory paths surrounding a central "ideal" trajectory. Implementation of this technique relies on item #4, as now described.

4. DSP Control

The above methods and theories are of little use without fast digital processing to implement real-time feedback control. We chose a Digital Signal Processor (DSP) approach, rather than a general purpose microprocessor, as best adapted to the task. We also took on the challenges of working with fixed-decimal and integer arithmetic, rather than floating point, as an economic necessity, particularly for small engines. We found a DSP family already tailored to motor control applications and developed appropriate interface circuitry. The ensuing process of hardware and software implementation has been laborious and time-consuming, and the results outstanding.