Magnesense Electromagnetic Engine Valve Technology: A Time for Transition

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Summary

The internal combustion (IC) engine is still with us. Over the next twenty years, improvements in this technology will be a critical part of our transportation and energy future. Magnesense offers a needed component for this future: fundamental improvements in the economy, simplicity, and reliability of electromagnetic engine valves. These computer-controlled intake and exhaust valves:

- improve gas mileage (by a demonstrated 15% and projected 20 to 25% with system optimization)
- reduce emissions of all kinds: HC (up to 50%), NOx (up to 50%), and CO_2 (by 15% or more)
- develop more peak power (about 15%) and more torque (about 20%) from the same size engine.

Why do engines with computer controlled valve timing work better? Two main reasons:

1. Broad range of near-optimum performance. Engine operation varies in two significant dimensions: **Variable RPM**, and **Variable Fuel-Air Charge** with each intake stroke (as controlled from the accelerator pedal.) Efficiency varies over this two-dimensional surface, peaking at one combination of RPM and fuel-air charge. Valve cams can be cut for optimization at one point on this surface, with efficiency dropping off anywhere else. Mechanical variable valve timing raises this efficiency surface at points removed from the optimized design point, broadening the range of near-optimum performance. Electromagnetic variable valve timing, under complete software control, can broaden the optimized range considerably more.

2. Reduced pumping losses. Fuel-air charge has previously been controlled by a throttle, which restricts the flow of air into the cylinder. Thus, as the piston passes bottom-dead-center and the intake valve closes, the cylinder air pressure usually reaches only a small fraction of one atmosphere. All the air in the cylinder has been "dragged" across a flow resistance, dissipating energy. The only operating point with minimal "pumping loss" is full throttle, meaning that the cylinder is allowed to fill completely, up to intake manifold pressure. Engines are seldom operated at full throttle, so significant energy is lost to throttling. With computer-timed electromagnetic valves, there is no throttle. The intake valve opens until the desired amount of air of fuel-air mixture is drawn in, then closes to prevent further inflow. For reduced power, the intake valve closes early, then the piston proceeds down to bottom-dead-center creating a partial vacuum, and then that vacuum pulls the piston partway back up until compression begins. The rebound of the piston, pulled by partial vacuum, contrasts with the more lossy response with throttled airflow.

The improvements arising from this increased range of near-optimum performance have been demonstrated by FEV in European road tests under standardized conditions comparable to the US EPA city/highway mileage tests.[1] Magnesense does not propose to invent, build, or market these valves.

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[1] Figures are backed by publications from the German company FEV (see overview at http://www.fev.com/index2.htm), whose prototypes meet the tough EURO3 emission standards and are approaching EURO4 figures.

We offer patented improvements in the design and control of existing electromagnetic engine valves that will make them good enough for widespread industry deployment. Our potential market includes any of several companies already developing these valves and needing our patents and expertise to make the valves good enough for commercial deployment. Companies (particularly FEV and Siemens) have done the difficult engineering of valve actuators. We offer improvements to help these companies move their valve technology to market.

What major problems do we address with our proprietary technology?

- Without servo control, electromagnetic engine valves can be noisy and wear out quickly.
- Servo control has heretofore required expensive and unreliable motion sensors and sensor wiring.
- The powerful springs needed for a high speed actuator consume valuable engine real estate.

Magnesense patents address the issues of sophisticated control software, elimination of sensor hardware, and a compact low-mass spring design. Separate patents on control software (pending) and control systems (issued in the US, granted in Europe) provide highly effective sensorless control. We avoid sensors and sensor wiring in the hot, vibration-ridden environment of the cylinder head. Our controller measures the electric current going out through the power wires to each solenoid, takes account of the controller's own sequence of output voltage settings, and solves electromagnetic equations to determine the solenoid position and velocity through time – without sensors.

We have an issued patent for a tested, compact, inexpensive spring that fits efficiently in the required form factor. Valve actuators must be narrow enough to stack side-by-side at the spacing of the cylinder valves. Their profile must be low enough to allow the hood to close. There is usually more space available in the remaining lateral dimension. Our spring design utilizes this lateral dimension very effectively, whereas the springs in competing designs stack vertically, leaving some lateral space under-utilized. Older designs replaced the conventional valve return spring with a much larger compression spring in the cylinder head, preloaded against an opposing compression spring in the top of the valve actuator. This led to large forces operating through the lash adjustment mechanism and a correspondingly large jump in required electromagnetic force just at the moment of valve closure. An approach by FEV goes to a three-spring design, restoring the valve return spring and lash adjustment of their former configuration. The Magnesense design replaces FEV's preloaded opposing compression springs with a push-pull spring requiring roughly the same vertical space as either one of the two FEV springs. Our spring configuration leaves more space for an efficient electromagnetic package. The entire actuator design them becomes a highly-compatible, compact bolt-in replacement for the mechanical components that now go under a valve cover. The automotive client saves years of engine redesign while actuator R&D is focused on a single bolt-in actuator package.

An existing dual-solenoid valve actuator requires four power wires and two sensor wires per valve. The proven Magnesense control technology eliminates the sensor and its two wires. Further opportunity exists to eliminate two of the four power wires and eliminate half of the expensive high-current switching transistors, along with their associated driver electronics. A patent has been issued for this method. Further development should demonstrate powering and controlling a valve actuator through just two wires instead of six.

We have an operating demonstration of our sensorless valve control system. It is a bench test of two valve actuators for a 5 HP engine. The controls of this demo are applicable on any scale, but besides application to automobiles, this specific demo opens a whole new field of improvement for small engines. The U.S. EPA sponsored part of this work focusing on small engines and is pleased with our results. Magnesense is stuck, however, in the timing and delays of grant funding cycles. Importantly, the EPA and other agencies want to see us hooked up with industry backers. Our era of self-funded research in this area is at an end. It is time for development with industry collaboration.

We feel that further development must be focused on a specific product. We have demonstrated a sensorless control system. We have demonstrated a magnetic actuator spring with low cost, a compact form factor, and superior performance. These "generic" demonstrations, operating in "laboratory" settings, need to be reconfigured for systems already developed and under test, in operating engines, by R&D departments in other companies.

Contextual Overview: Where Magnesense Technology Fits

We at Magnesense see five broad areas for IC engine improvements, with some overlaps and interactions:

1. Hybrid gasoline-electric systems
2. HCCI operation (Homogeneous Charge, Compression Ignition)
3. Diesel
4. Total rethinking of small engines
5. Electromagnetic engine valves

Hydrogen fuel cells are a vision for a more distant future. We foresee serious problems with that vision, which are beyond the scope of this paper. Detailed projections aside, it is arguable that major deployment of hydrogen is at least twenty years in the future, if ever. Let us focus on the above five near-term options, specifically in relation to the Magnesense electromagnetic valve technology.

1. **HYBRIDS:** IC engines are most efficient when designed for a single operating point, un-throttled at full power and operating at a single design RPM. Throttling introduces pumping losses, reducing efficiency This is just one reason why engines operating an a small fraction of full power are quite inefficient. Using a larger engine to meet peak power needs and then throttling operation for lower power most of the time is inefficient. The "ideal" hybrid engine design uses a small IC engine operated at full power and then shut down intermittently, with a battery and motor system to provide acceleration power, recover energy from braking, and buffer differences of power supply and demand.

A major barrier to full hybrids is the trunk load of batteries, which are expensive, wear out, and whose manufacture is far from environmentally friendly. Supercapacitors add flexibility to the mix, storing and releasing energy very efficiently – and they don't wear out. For equivalent size, however, supercapacitors don't store as much energy. There is a spectrum of hybrid designs extending from "plug-in hybrids" to "mild hybrids" with differing mixes of engine power and energy storage. Electromagnetic valves become increasingly important where there is less emphasis on energy storage and, consequently, greater dependence on a variable range of engine performance. Magnesense technology has an important niche in this hybrid vehicle scenario.

2. **HCCI:** HCCI offers the best aspects of diesel and SI (Spark Ignition) engine technologies. As in an SI engine, fuel and air are thoroughly mixed prior to combustion. As in a diesel engine, the fuel is ignited by the temperature increase accompanying a high compression ratio (HC**CI**: "Compression

Ignition"). Unlike a diesel, the fuel is pre-mixed (**HC**CI: "Homogeneous Charge") with both air and recirculated exhaust gas. The burn is lean, efficient, and complete, since the combustion components are well mixed, so there is little unburned HC and CO generation. The temperature is uniform and controlled by a regulated dilution of the mixture with recirculated exhaust gas, controlling the peak combustion temperature and minimizing hot spots that tend to produce NOx pollutants. Because of the constraints to make HCCI work and cause auto-ignition to occur at the correct moment, a "pure" HCCI engine only works over a very limited power range. A practical HCCI engine would still include a spark plug and would transition momentarily to conventional SI mode to meet peak power demands.

The problem with HCCI is control of this rather unstable process. HCCI researchers recognize that control will require some form of variable valve timing. To stabilize HCCI, we believe that valve timing must be controlled for each individual piston cycle, compensating for instabilities before they grow. Mechanical variable valve timing techniques are not up to this task. The speed and flexibility of electromagnetic valve control will be required. The magazine "Car and Driver" views HCCI as the internal combustion technology of the future. Magnesense holds a critical component for this future.

3. **DIESEL:** Diesel has undergone revolutionary improvements. Its efficiency is competitive with camless SI engines using electromagnetic engine valves. Automotive deployment of diesel is high in Europe and low in the US, for institutional reasons. Europe has deployed low-sulfur diesel fuel, which is necessary for operation with catalytic converters. U.S. diesels, operated with fuels that would foul a catalytic, are dirty and allowed to continue only because there is no alternative for operation of our large fleet of trucks and locomotives. Diesel and electromagnetic valves are a poor match – larger forces are required than are readily obtained in a purely magnetic actuator. In fact, electro-hydraulic variable valve timing is being deployed in the truck market (by Colorado-based Sturman Industries). These valves accomplish the same result as non-hydraulic solenoid valves, but at a higher cost and only in an environment where hydraulic power is available. Improved diesel engines, with or without electro-hydraulic valve actuation, are potential future competitors with electromagnetic valves in SI engines, particularly for vehicles intended principally for highway operation (where hybrids with regenerative braking offer little advantage.) In the European auto market, electromagnetic valve technology and diesel technology are likely to develop in parallel, as competitors, while diesel cars are unlikely to make significant inroads in the US market for some time.

4. **SMALL ENGINES:** Small engines, including lawnmowers and tractors, outboards, jet skis, snowmobiles, etc., are in a class facing increased regulatory pressure with limited technology alternatives. Fuel injection, exhaust gas recirculation (EGR), oxygen sensors, and catalytic converters are too expensive for current small engine markets and would be politically difficult to force onto the market by regulation. As a specific focus for its research into electromagnetic valve control, Magnesense has concentrated on design of a system for small engines. We chose a single-cylinder two-overhead-valve 5-HP Honda engine as well-suited to prototype development. Honda is one of several potential customers for the result. We have an inexpensive system running the valves on the Honda cylinder head in a lab bench setting. While the valves have been developed to the point of fully controlled actuation, they have not yet been integrated into the operation of the engine running and burning fuel.

- Computer timing of valves will eliminate the carburetor and throttle plate, making way for a simplified no-moving-parts carburetor.
- Valve timing will interact with carburetion to give computer control of both the fuel/air charge and the ratio mixture, without going to the expense of fuel injection.

- Exhaust valve timing will control the retention of exhaust gas for controlled EGR, without introducing extra hardware for a regulated external EGR circuit.
- The valve control microprocessor will simultaneously provide optimized spark timing.
- Our valve controller has the potential (beginning to be realized in experimental operation) for sensing combustion variables: specifically by sensing gas pressures and flow forces that affect servo-controlled valve motion. This sensing is expected to lead to automated control of fuel mixture without the use of an oxygen sensor.
- Our electronics package would control adaptive spark advance and use valve timing to govern engine speed, sense and regulate intake air flow and fuel mixture, and control EGR.

Although a small engine with a Magnesense electromagnetic valve system would cost more than present engines of the same power rating, that system promises to cost much less than a catalytic converter. Our inexpensive digital valve control prototype starts with a DSP (digital signal processor) whose equivalent now sells for under $3 in OEM quantities. With capability for both full and partial compression relief, these valves would make a small pull-start lawnmower engine very easy to start, with the electronics booting up from generator or alternator power with a single tug of the starter rope (starting small no-battery lawnmowers with one easy pull.) We believe that with camless electronic valve and spark timing, pollution can be reduced at the source sufficiently to make a catalytic converter unnecessary.

An advantage of going after the small engine market is that there is so much room for improvement. It has been estimated that on a per-gallon basis, typical small four-stroke engines emit 100 times as much pollutant as automotive engines. Two-stroke engines are worse. It has been recognized that in regions like the Los Angeles basin, lawnmowing contributes significantly to overall air pollution. Here is an area where the emerging Magnesense technology could fulfill a need and meet future regulatory requirements with little competition – we are unaware of good existing alternatives to our solution. The EPA appears to agree with this assessment.

5. ELECTROMAGNETIC ENGINE VALVES: Mechanical variable valve timing is being incorporated into an increasing proportion of production automotive engines, for instance, the Honda VTEC engine. Typically, variable mechanical timing only goes so far as to advance or retard the effective camshaft phase, adapting to gas flow conditions at high and low engine RPMs. Computer controlled solenoid valves can accomplish considerably more, replacing the function of the throttle plate, eliminating the pumping losses associated with a less-than-wide-open throttle, varying the effective compression ratio for maximum usable compression (without pre-ignition) under different conditions of intake air temperature and the like, and achieving controlled EGR using exhaust valve timing. Magnesense owns the control technology to bring electromagnetic valves within practical and economic reach. We believe that this technology will be deployed alone and in combination with hybrid engine designs. For cars and small trucks that see principally highway use, we expect the market to be dominated by non-hybrid camless engines using electromagnetic engine valves. For urban-oriented automotive markets, we foresee predominance of hybrids using electromagnetic engine valves and some combination of battery and supercapacitor energy storage. While full hybrids will have a place, particularly for taxis and other highly urban-oriented stop-and-go vehicles, we do not foresee full hybrid vehicles as being the "automobiles of the future." Most hybrids will require significant variation in engine power output, thus benefiting from electromagnetic variable valve timing. We foresee hydrogen fuel cell vehicles only in the distant future, or never, as unforeseen alternatives may arise.

Current Status of Magnesense LLC

Existing IP:

- Software-driven control system operating valve hardware on a bench.
- Soft-landing engine valves under cheap real-time Digital Signal Processor (DSP) control.
- Our control is “sensorless,” inferring position and velocity from electrical parameters.
- Our technology is protected by 5 issued U.S. patents, 1 granted Euro patent (to issue in four countries), and 2 pending U.S. patents, varying from “moderately significant” to “ground breaking” (as we are prepared to discuss).

Marketing issues:

- Our control technology offers possibly the best performance/cost combination on planet Earth for electric valves.
- Electric valve technology has been demonstrated to improve fuel economy, cut emissions, and improve engine performance.
- The technology is adaptable to multiple fuels.
- These technologies have the potential for low cost, simplicity, speed, and long valve life due to excellent control for low impact – improvements that could finally bring electromagnetic engine valves out of R&D and into the automotive marketplace.
- Our inexpensive bench system could be adapted to the existing high-end small engine market while positioning itself as the most viable way to meet future emissions standards. The US EPA reviews of our work back this assertion.

These points are illustrated and detailed in greater depth at our website: www.magnesense.com.