Electromagnetic Fully Flexible Valve Actuator

A traditional cam drive train, shown in Figure 1, acts on the valve stems to open and close the valves. As the crankshaft drives the camshaft through gears or a belt, the timing of the opening and closing of a valve is controlled by the cam design and is fixed relative to the piston position. This means that the engine performance is optimized only over a narrow range of engine speed. Existing electromagnetic valve actuators focus on variable timing (the ability to open and close the valves at will) however, they do not allow for variable lift. Our approach, shown in Figure 2, allows for fully flexible valve control (i.e. both, variable timing and lift, and low valve landing speed, which will produce a quieter engine).

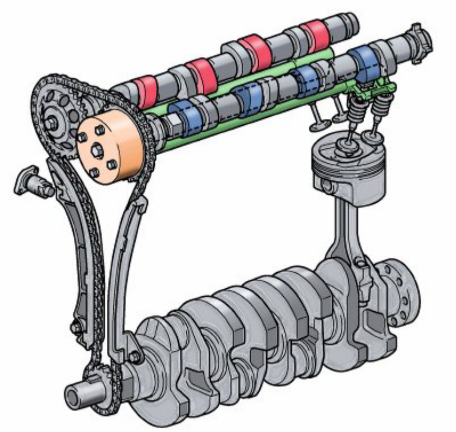


Figure 1. Traditional Mechanical Cam Drive Train (*now made obsolete*)

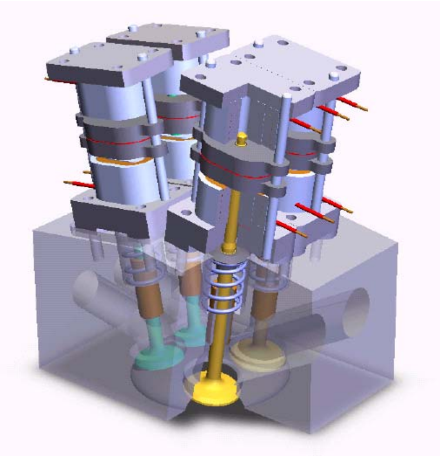


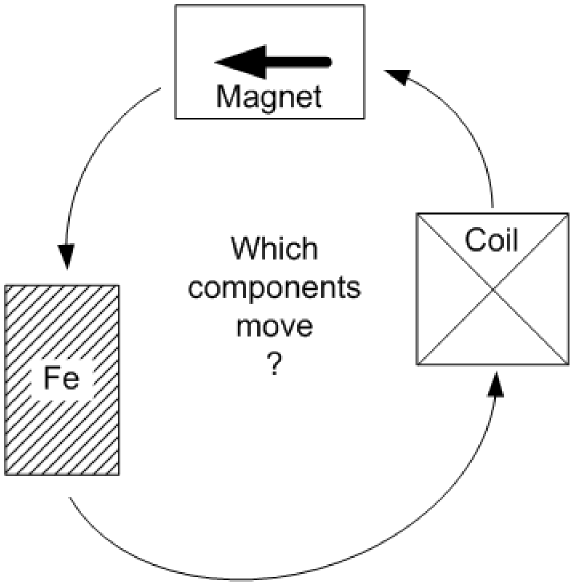
Figure 2. Electromagnetic Fully Flexible Valve Actuator

Electromagnetically-controlled valves can operate optimally at all engine speeds, torque levels, and temperatures thereby greatly improving the engine performance, including emissions. For example, greater than 20% improvement in fuel economy is expected for fully flexible electromagnetic valve actuators.

Design and analyses

Actuator Configurations—Introduction

As shown in the adjacent figure, a common issue for actuator design is which components move relative to an external body and which other components are stationary? Typically there are two possibilities: (1) moving magnets (MM) and stationary coil, or (2) moving coils (MC) and stationary magnets. As discussed in the following sections, we have developed another option, (3) moving plunger (MP) and stationary coil and magnets.



Typical operation of an engine might average 2000 rpm for 15,000 miles/year, which equates to approximately 30 million actuation cycles/year. A MC configuration has potential issues with flexing of electrical leads, and a MM configuration has potential issues with magnet mechanical damage (fatigue or cracking) due to the constantly reversing acceleration profile. Therefore, a configuration without either of these components moving is indeed attractive. A MP configuration can be made extremely rugged and able to withstand the high acceleration cycles. Furthermore, the stationary magnets and stationary coil can be electrically, thermally and mechanically buffered to some extent within their environment.

Ricardo WAVE Analyses

Ricardo WAVE analyses provided the starting point for the design of the electromagnetic valve actuator (EVA). For feasibility demonstration purposes and since this provides most of the benefit of using EVAs, only the intake valve was analyzed. A simulation was performed of a Ford Ranger 4-cylinder engine operated at different speeds. Simulation outputs included the crank angle, cylinder pressure, valve lift, pressure across the valve, friction work, and total force experienced by the valve during motion. Because the largest forces are due to fuel combustion and the combustion pressure tends to more securely seat the valve, the actuator does not have to overcome these very high forces. Figure 3 shows the valve force and valve lift from Ricardo WAVE simulation. The actuator is initiated where the figure is marked “Intake cycle begins.” It is evident that the greatest actuator forces requirements originate from the high rpm motion of the valve.

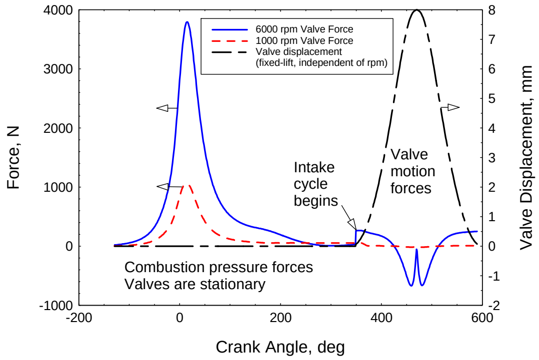


Figure 3. Ricardo WAVE Simulation Results

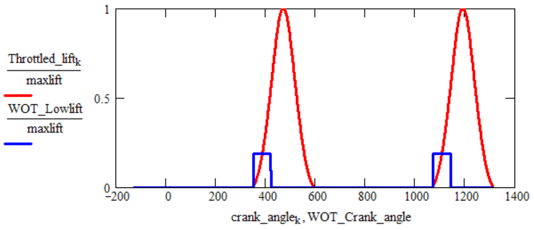


Figure 4. Fully Flexible Valve Actuator Enables Wide Open Throttle combined with Low Valve Lift

The Ricardo WAVE simulation was also used to verify the utility of the idea of wide open throttle (WOT) combined with low valve lift. The central theme of the concept is to eliminate another mechanical subsystem (the throttle) in addition to eliminating the mechanical cam drive train sub system. Without variable valve lift the engine would receive an excess of air-fuel mixture and would not operate properly at low speeds. Figure 4 shows a comparison of the desired low speed valve displacement profiles for two cycles with WOT. Note that the valve opens at the same time as in a throttled lift case, but the lift is much less (approximately 20% of full lift) and of much shorter duration. WOT capability significantly improves engine low rpm characteristics.

A Pressure-Volume (PV) plot of engine cycle shows that WOT improves engine fuel economy. This type of plot is commonly used for evaluation of thermodynamic cycle efficiency. The fundamental idea is the WOT reduces the required work input to the engine and thereby increases the net engine output. Figure 5 illustrates the idea. The green area is work output and the red area is work input required for cycle operation. WOT reduces the work input from the large red area to the much smaller yellow area. Figure 6 gives actual Ricardo WAVE simulation results of WOT operation. The dark blue curve is the traditional throttled-cycle and the magenta is the wide-open-throttle cycle. As indicated on the figure, a 12-13% increase in fuel economy is made possible by this technique alone, enabled by the fully flexible EVA.

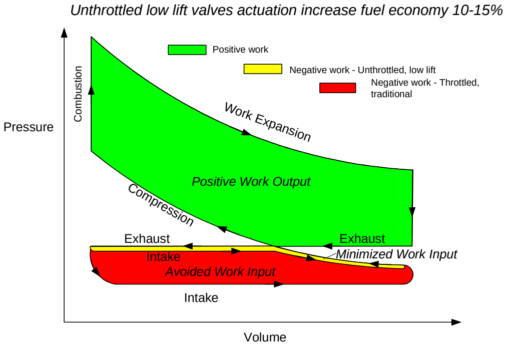


Figure 5. Wide Open Throttle Theoretical Efficiency Improvement

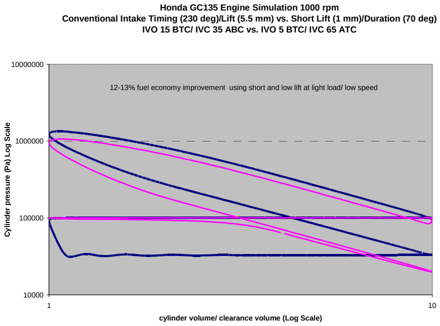


Figure 6. Calculated Wide Open Throttle Benefits

Simulation

The actuator was simulated in Simulink®. The simulation was exercised for different engine operating speeds. As mentioned above, the most challenging is the high speed operation. For the demonstration actuator, Figure 7 gives a close-up of the valve displacement as a function of time for the fastest transition time. Figure 8 shows the commanded position, valve force, and resulting simulated valve displacement.

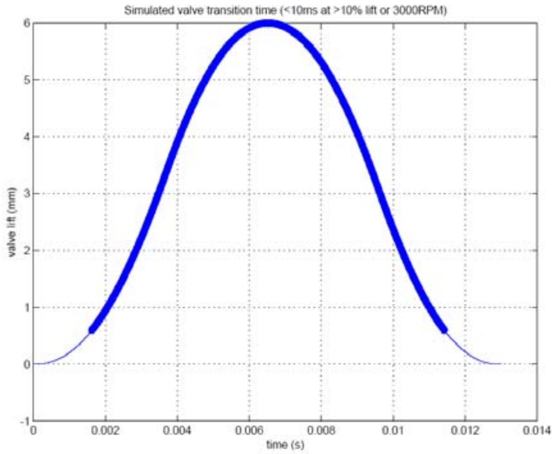


Figure 7. Demonstration Actuator Rapid Open-Close Transition

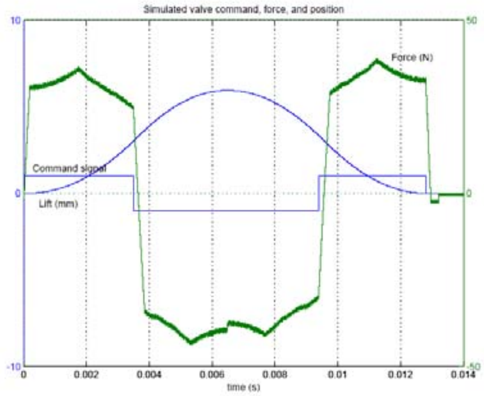


Figure 8. Detailed Simulation Results for the Rapid Transition: Commanded signal, Total valve force, and Valve displacement.

Magnetic Finite Element Analyses

As mentioned above, the central concept of the actuator admits to several quite different configurations. Commercial magnetic finite element analysis software (Ansoft's Maxwell® 3-D and Optimetrics™) was utilized to input the various configurations and analyze the performance of each configuration. In addition, using the Optimetrics™ component, we performed optimization of each configuration. The central idea of Optimetrics is an automated way to numerically determine the sensitivity of a design configuration to a defined "goodness" parameter and then to continue to refine the design in the "direction" of increasing goodness. When the design space is large, there are simply too many possible permutations of design variables to compute each one individually. For example, there are more than one dozen individual dimensional characteristics which collectively, with materials choices and boundary conditions, define a single design. If 6 values of each dimension were to be analyzed, almost three million design combinations would result for each configuration. This is too many to seriously evaluate and would represent analyst overload. Instead, Optimetrics essentially calculates the greatest slope toward increasing goodness and marches along that path. Localized extremes were encountered and dealt with by utilizing multiple starting designs to verify convergence to an optimized specific design combination.

We examined nine (9) design configurations. We compared the configurations based upon the computed maximum value acceleration divided by the square root of dissipated power, $A/\sqrt{P}$. The valve acceleration is computed by computing the electromagnetic force and dividing it by the sum of moving masses of the valve, the valve stem, and connecting hardware. [Note: other bases for comparison could, of course, be used. Through design optimization, alternative metrics would alter the actuator design details.] The MFEA simulation takes current density in the coil as an input and calculates the coil resistance and electrical power consumed. Several of the configurations can be employed as either MM or MC. There are, of course, many parameters upon which the value of $A/\sqrt{P}$ depends, and the utility of the actuator is not described solely by this parameter. Therefore, although we considered heavily the value of $A/\sqrt{P}$ in determining which configuration to build for the feasibility demonstration, we also considered aspects such as expected actuator reliability and longevity.

Based upon this analysis, the final actuator design is markedly superior to the other designs. Fundamentally this is because the moving portion is simply a steel plunger of relatively small radius and relatively high magnetic saturation value. This design, once properly engineered for the environment, is expected to have an excellent reliability record because of its simple, robust nature.

Experimental Setup and Results

Actuator Construction and Engine Preparation

After optimizing the configuration and geometry of the actuator and running dynamic simulations, a valve actuator was fabricated and installed on a single-cylinder engine. A drawing of the single-cylinder engine selected for this demonstration project is shown in Figure 9. Selection criteria for the engine were: relatively low power (4-hp), light weight, and ease of access to the valves. This engine was particularly easy to modify the valve since it has both overhead cams and overhead valves.

Experimental Results

Feasibility of operating an internal combustion engine based upon the designed electromagnetic valve actuator was demonstrated. An increasingly difficult series of actuator tests consisted of operating the actuator: on a bench top, in the unassembled cylinder head, statically on the engine (assembled), slow motion on the engine (hand crank), fast motion on the engine (pull-cord operated), and during combustion. Limited space dictates that the most relevant tests are reported here.

Single Cylinder Engine Operation

Operation of an engine with the actuator controlling the intake valve was the major goal of this feasibility demonstration project. Figure 10 shows the valve displacement during the cycle as a function of crank angle from an early run. Twin desirable attributes of high opening speed (~890 mm/sec) and low landing speed (~30 mm/sec) are evident in the figure. It should be remarked that the actuator operated the first time the engine was started and the engine runs reliably, although changing engine speeds requires a manual adjustment in valve commands.

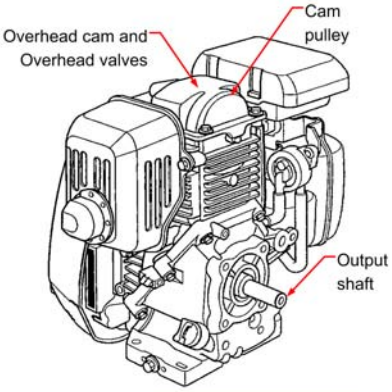


Figure 9. Honda GC135QHA Engine

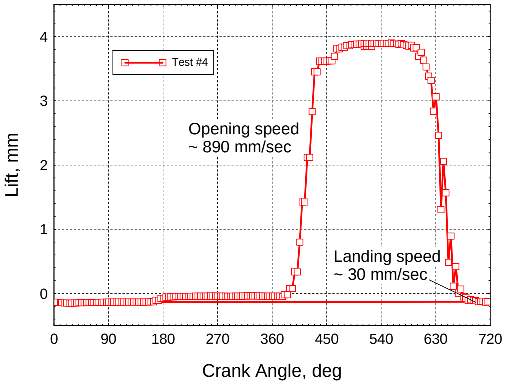


Figure 10. Valve Displacement vs Crank Shaft Angle

Figure 11 and Figure 12 show the actuator mounted on the engine.

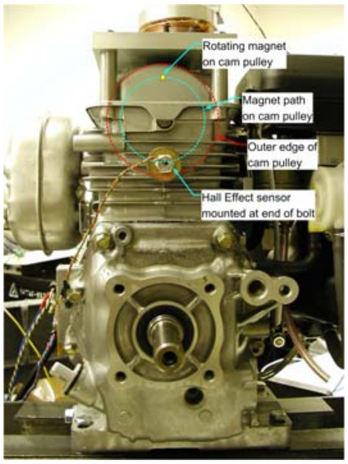


Figure 11. Phantom Views of Cam Magnet Path

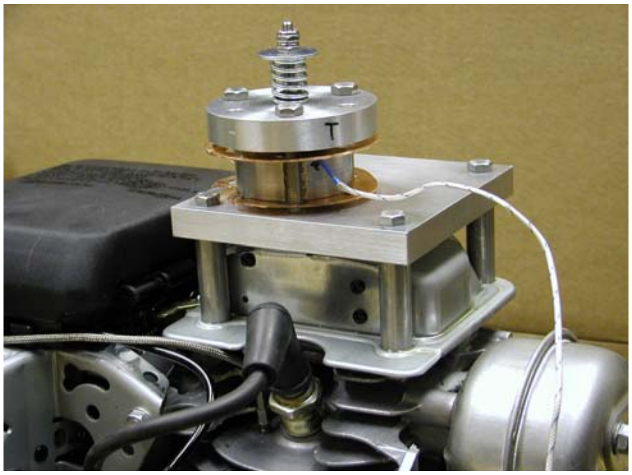


Figure 12. Electromagnetic Valve Actuator mounted in Engine

Conclusions

In conclusion, the major goal of designing, building, and testing an electromagnetic valve actuator was achieved. The design process involved many configurations with moving magnets, moving coils, and/or a moving plunger. The selected design was significantly above other designs we analyzed based on kinematic performance (acceleration per square root of dissipated power) and had desirable characteristics such as stationary magnets and stationary coil.

A dynamic simulation was created to predict performance of the valve under a variety of conditions, especially varying the engine speed.

The detailed manufacturing drawings were made and an actuator was fabricated and assembled. A single-cylinder engine was chosen and modifications were made to the cylinder head to mount the actuator and various sensors. A series of run-up tests were performed culminating in the feasibility demonstration of engine operation under electromagnetic intake valve actuator control. The test results shows the actuator exhibits the inherent advantages of the fully flexible electromagnetic valve actuator such as fast valve-opening speed and low valve-landing speed.

Electromagnetic actuator protected by US Patents #6,828,890; #6,876,284 and other patents pending.