ENVERA VARIABLE COMPRESSION RATIO ENGINE

FINAL REPORT

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ENVERA LLC

Envera LLC was awarded Cooperative Agreement Instrument number DE-FC26-05NT42484 from the National Energy Technology Laboratory, US Department of Energy (NETL, DOE) for the project titled Low Cost Fast Response Actuator for Variable Compression Ratio Engines. Charles Mendler, President of Envera LLC is the project director and principal investigator

BACKGROUND ON VCR TECHNOLOGY

Aggressive engine downsizing, variable compression ratio and use of the Atkinson cycle are being combined to improve fuel economy by up to 40 percent relative to port fuel injected gasoline engines, while maintaining full engine power.

Approach

Engine downsizing is viewed by US and foreign automobile manufacturers as one of the best options for improving fuel economy. While this strategy has already demonstrated a degree of success, downsizing and fuel economy gains are currently limited. With new variable compression ratio technology however, the degree of engine downsizing and fuel economy improvement can be greatly increased. A small variable compression ratio (VCR) engine has the potential to return significantly higher vehicle fuel economy while also providing high power. Affordability and potential for near term commercialization are key attributes of the Envera VCR engine.

VCR Technology

To meet torque and power requirements, a smaller engine needs to do more work per stroke. This is typically accomplished by boosting the incoming charge with either a turbo or supercharger so that more energy is present in the cylinder per stroke to do the work. With current production engines the degree of engine boosting (which correlates to downsizing) is limited by detonation (combustion knock) at high boost levels. Additionally, the turbo or supercharger needs to be responsive and efficient while providing the needed boost.

VCR technology eliminates the limitation of engine knock at high load levels by reducing compression ratio to ~9:1 (or whatever level is appropriate) when high boost pressures are needed. By reducing the compression ratio during high load demand periods there is increased volume in the cylinder at top dead center (TDC) which allows more charge (or energy) to be present in the cylinder without increasing the peak pressure. Cylinder pressure is thus kept below the level at which the engine would begin to knock. When loads on the engine are low the compression ratio can be raised (to as much as 18:1) providing high engine efficiency. It is important to recognize that for a well designed VCR engine cylinder pressure does not need to be higher than found in current production turbocharged engines. As such, there is no need for a stronger crankcase, bearings and other load bearing parts within the VCR engine.

Both engine down-sizing and the Atkinson cycle are used to improve fuel efficiency

The Envera VCR engine will also include variable valve control. With variable valve control the Envera VCR engine will operate most of the time using the more efficient Atkinson cycle. When high torque values are required the valve settings are adjusted to maximize the amount of intake air trapped in the cylinders, as needed for maximizing power and torque.

While variable valve control (VVC) is highly beneficial, it is not a desirable method for adjusting the engine compression ratio. VVC can adjust the “effective compression ratio” by adjusting the amount of air trapped in the cylinder. Trapping more air in the cylinder provides a higher effective compression ratio and more power. Trapping less air in the cylinder provides a lower effective compression ratio and less power. Unfortunately, the opposite compression ratio values are needed. A low compression ratio is needed at high power to avoid detonation, and a high compression ratio is needed at low power levels to provide higher engine efficiency. VCR is unique in its ability to provide the correct compression ratio when needed. Unlike VVC systems, the Envera VCR mechanism adjusts the physical size of the combustion chamber and is able to provide the ideal compression ratio settings at all power levels.

The best solution is to combine VCR and VVC. With this approach much higher efficiencies are attained at low load by increasing the mechanical compression ratio with VCR, reducing pumping losses with VVC, and operating the engine using the high-efficiency Atkinson cycle. Attaining high power output is also important for improving fuel economy, because increased power output permits large engines to be replaced with smaller engines that return higher efficiency under most driving conditions. High power output levels are attained by reducing compression ratio with the VCR to avoid detonation, boosting the engine, and adjusting the valve timing with the VVC to trap as much intake air as possible in the engine cylinders.

Brake specific fuel consumption under 230 g/kWh from 10 to 70 horsepower for a 1.8L engine was previously demonstrated[3]. The Envera VCR engine is projected to attain similar efficiency below 70 hp. As illustrated in Figure 1, attaining high efficiency at small power levels is essential for attaining high fuel economy, because only rarely are engines operated at higher power levels in light duty vehicles. A goal is to attain 40 percent higher efficiency than some production V8 engines at 30 hp. Occasionally high power output is required from the engine. The Envera VCR and boosting are used to attain a V8 like torque curve to meet these occasional high power demands.

In addition to boosting and VVC other technologies such as cooled exhaust gas recirculation (EGR) and gasoline direct fuel injection (GDI) are also compatible with VCR. VCR technology is also highly beneficial for multi-fuel engines, and could lead to accelerate use of alternative and renewable fuels both in the United States and over seas.

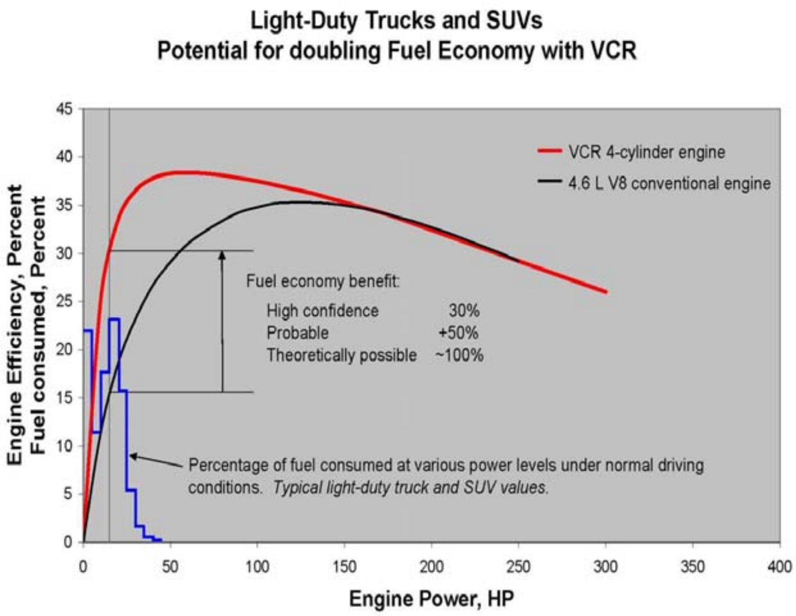

Figure 1. VCR technology and aggressive engine down-sizing are used to greatly increase fuel economy.

Fuel efficiency comparison

The fuel efficiency benefit of down sizing from a naturally aspirated V8 engine to a turbocharged V6 engine was assessed by the US Environmental Protection Agency (EPA)[1] and Ricardo[2]. In Figure 2 engine efficiency projections for an in-line 4-cylinder Envera variable compression ratio engine are added to the earlier EPA/Ricardo comparison.

Figure 2 includes brake specific fuel consumption (BSFC) curves for a gasoline direct injection turbocharged 3.6L V6 engine (DI Boost) and a naturally aspirated engine 5.7L V8 engine (V8) as reported by EPA[1]. Envera LLC has added to the graph an efficiency projection for its variable compression ratio engine (black dashed line). All three engine BSFC curves correspond to an engine speed of 2000 rpm.

The Envera VCR engine will operate according to the Atkinson cycle at light load, with engine calibration settings largely similar to that of the 2010 Toyota Prius. The solid portion of the "--- VCR Boost" curve is drawn from engine efficiency date presented by Toyota in SAE paper 2009-01-1061[3]. The date has been scaled from an engine having a displacement of 1.8 L (the stock 2010 Toyota Prius) to 2.2 L so that the peak torque of the Envera VCR engine matches the peak torque of the V8 engine at 2000 rpm, which is 445 Nm (328 ft-lb).

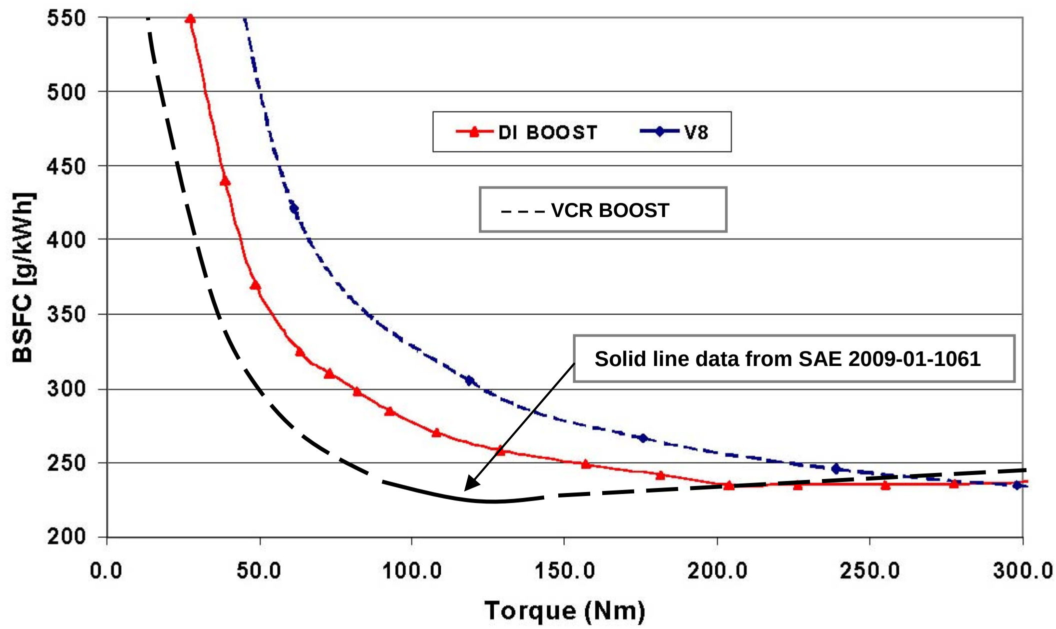

Figure 2. Fuel efficiency comparison of a 5.7L V8, a 3.6L Turbo-DI V6, and a 2.2L VCR 4-cylinder engine (projected data).

In this comparison the Envera VCR engine employs supercharging in order to provide V8-like torque at low engine speeds. VCR and variable valve control enable the Envera engine to operate according to the high-efficiency Atkinson cycle at light loads, and according to the Otto-cycle with aggressive supercharging at high loads. Data for the three engines is as follows:

Type	V8	V6-Turbo DI	I4-Supercharged VCR
Displacement	5.7L	3.56L	2.2L
Power	298 kW	283 kW	271 kW
At 2000 RPM:			
Peak Torque	445 Nm	560 Nm	445 Nm
Peak BMEP	9.8 bar	19.7 bar	25.4 bar
Fuel efficiency @ 100 Nm	328 g/kWh	275 g/kWh	230 g/kWh

At 100 Nm and 2000 rpm, all three engines produce about 28 horsepower. The V6-Turbo DI engine is expected to consume 19.6 percent more fuel than the I4-Supercharged VCR engine at 100 Nm. The V8 engine is expected to consume 42.6 percent more fuel than the I4-Supercharged engine at 100 Nm. Actual mileage gains will depend on the vehicle model and duty cycle.

Lowering Emissions

Cold start emissions are the single largest source of hydrocarbon emissions from automobile engines. Before the catalytic converter warms up, hydrocarbon (HC) emissions are generally proportional to engine displacement, so smaller engines have significantly lower cold start emissions than larger engines all else being equal. Reducing engine size with VCR technology is highly beneficial both for improving fuel economy and for reducing cold-start HC emissions.

During high-power conditions, intercooling and cooled exhaust gas recirculation (EGR) are being used to attain low nitrous oxide (NOx) emission levels and prevent catalytic converter overheating. Emissions testing of the VCR engine was conducted under earlier Department of Energy programs. In a first study emissions were generally similar to conventional spark-ignition engines. In a second more recent study NOx emissions were found to decrease with the VCR. The reason for these favorable results is not fully understood, and will be examined in more detail during future engine testing.

The Envera Variable Compression Ratio mechanism

The Envera VCR mechanism uses an eccentric carrier approach to adjust engine compression ratio. The crankshaft main bearings are mounted in this eccentric carrier or “crankshaft cradle” and pivoting the eccentric carrier 30 degrees adjusts compression ratio from 9:1 to 18:1. The eccentric carrier is made up of a casting that provides rigid support for the main bearings, and removable upper bearing caps. Oil feed to the main bearings transits through the bearing cap fastener sockets. The eccentric carrier design was chosen for its low cost and rigid support of the main bearings.

A control shaft and connecting links are used to pivot the eccentric carrier. The control shaft mechanism features compression ratio lock-up at minimum and maximum compression ratio settings. The control shaft method of pivoting the eccentric carrier was selected due to its lock-up capability. The control shaft can be rotated by a hydraulic actuator or an electric motor. The engine shown in Figures 3 and 4 has a hydraulic actuator that was developed under the current program.

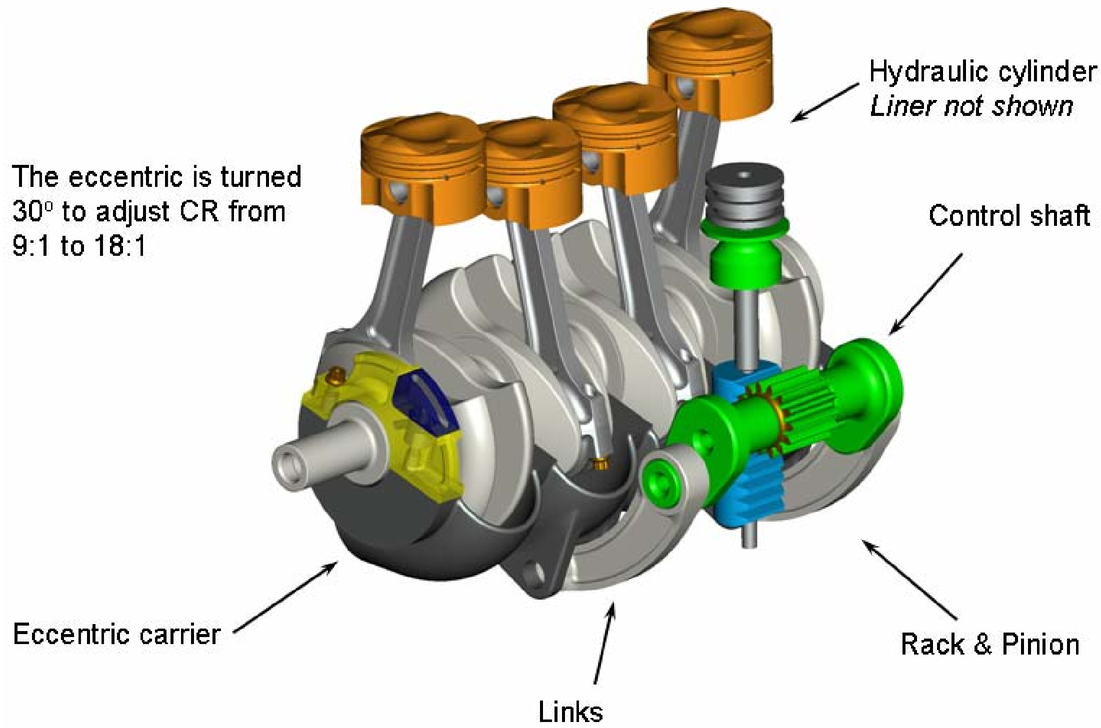

Figure 3. Envera variable compression ratio mechanism.

Low Cost Architecture

In-line 4-cylinder engines are significantly less expensive than V engines because an entire cylinder head can be eliminated. The cost savings from eliminating cylinders and an entire cylinder head will notably offset the added cost of the VCR and supercharging. Replacing V6 and V8 engines with in-line VCR 4-cylinder engines will provide high fuel economy at low cost.

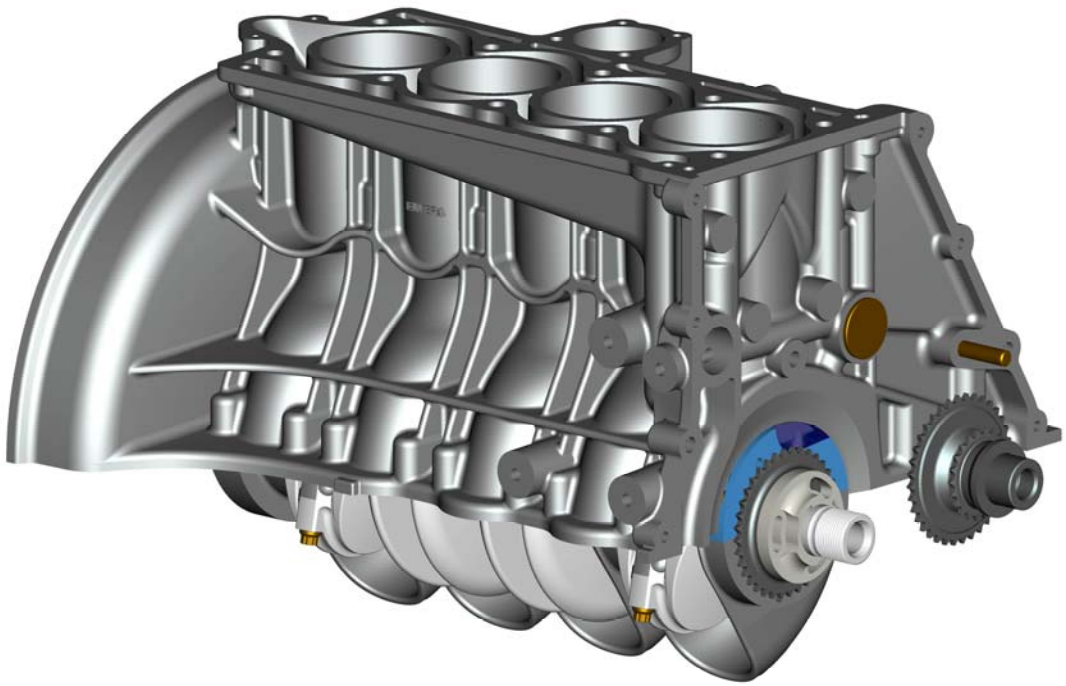

Figure 4. Envera VCR Crankcase.

Summary

Numerous enabling technologies exist which have the potential to increase engine efficiency. The greatest efficiency gains are realized when the right combination of advanced and new technologies are packaged together to provide the greatest gains at the least cost. Aggressive engine downsizing with variable compression ratio and use of the extended Atkinson cycle can provide large fuel economy gains that are exceptionally cost effective.

Analysis indicates that a 2.2L supercharged Envera VCR engine can match the torque of a larger V8 engine at 2000 rpm. The VCR engine's high torque value at low engine speed is beneficial for maintaining the driving feel and responsiveness of the larger V8 engine. The Envera VCR engine will attain high efficiency at ~100 Nm primarily due to the combination of engine down-sizing and use of the Atkinson cycle. Qualitatively the fuel economy gain realized from down-sizing from a V8 to an Atkinson-cycle I-4 is about twice as large as the benefits from down-sizing from a V8 to a Turbo V6 when evaluated at 100 Nm 2000 rpm.

INTRODUCTION TO THE ENVERA / NETL PROGRAM

For variable compression ratio engines to be successful in the market place, the VCR mechanism must have a low cost and be able to adjust compression ratio quickly. The Envera / NETL cooperative research and development program was directed towards the development of the actuator used for adjusting the pivot angle of the eccentric carrier in the VCR engine. The program goal was to develop a low cost and a fast response actuator for the Envera VCR engine.

PHASE 1 DEVELOPMENT

Prior to the current program Envera initiated development of a 4-cylinder 1.8L VCR engine that includes a hydraulic actuator for adjusting engine compression ratio. Mechanical loading on the engine's actuator system was evaluated in Phase 1 of the NETL program. The evaluation was conducted using:

ProEngineer	Part and mechanism assembly
ProE MDO Extension	Dynamic force analysis
GTPower	Gas force on the piston (Prior data)
Origin 7.5	Data conversion

Dynamic loads were modeled at five conditions:

2000 rpm	4bar bmep	Low CR
2000 rpm	4bar bmep	Mid CR
2000 rpm	12bar bmep	Mid CR
6000 rpm	4 bar bmep	Mid CR
6000 rpm	12bar bmep	Mid CR

The pressure inside the VCR hydraulic actuator were calculated. The bore diameter of the hydraulic cylinder is 34.925 mm (1 3/8 inches). The 2000 rpm 12bar bmep condition causes the highest loading on the hydraulic system. Figure 5 shows a maximum hydraulic pressure inside the hydraulic cylinder of about 2250 psi. At higher engine speeds the loads are reversing and peak loads smaller due to the inertial effects of the piston.

As can be seen in Figure 5, the hydraulic cylinder pressure is under 400 psi for 2/3rds of the crank angle rotation. Under the original proposal submitted to NETL on November 4, 2004, a system of check and control valves was planned to control flow of oil into the cylinder when pressures were generally under about 400 psi.

The analysis showed a peak hydraulic pressure larger than desirable for attaining a low cost fast response actuator system. In view of the high cylinder pressures, a development effort was initiated to reduce the size of the hydraulic pressure spikes through system optimization. Through this effort peak hydraulic pressures were significantly reduced. In Phase 1 peak cylinder pressures for the optimized system were estimated to be 314 psi.

Phase 2 analysis indicates that a slightly higher hydraulic pressure of 520 psi will be needed, or alternatively a slightly larger hydraulic cylinder may be used. The 520 psi represents a 76 percent reduction in peak pressure. The reduction in peak pressure represents a major program accomplishment. Figure 6 shows the estimated hydraulic cylinder pressure of the newly optimized hydraulic system.

Peak pressures were reduced in the hydraulic actuator system by increasing the hydraulic cylinder bore to 50.80 mm, reducing the eccentric off-set dimension, and enabling the actuator system to lower but not increase compression ratio during high brake mean effective pressure (bmep) conditions.

Some light-duty trucks and SUVs have transmissions equipped with an intermittent high-pressure hydraulic capability. This high-pressure oil supply could optionally be used to power the VCR actuator, and thereby eliminate the need for a dedicated VCR hydraulic oil pump. Initially, however, a dedicated oil pump is desirable.

A test rig was built and tested to evaluate actuator response time. Crankshaft travel from high to low compression ratio is 6.5 mm. Corresponding hydraulic ram travel is 69.5 mm. Mass was added directly to the test rig to simulate VCR hardware mass, and the inertial resistance to changing compression ratio. The inertial mass is in the order of 45 kgs. To simulate the inertia, approximately 4.5 kgs could be added to the test rig ram, which travels approximately ten times further than the adjustment of the crankshaft position. The 4.5 kg mass is assumed to be trivial for the purposes of Phase I testing relative to the maximum actuator ram force of ~4893N (1100 lbf).

Design improvements for attaining the lower hydraulic pressures were incorporated into the test rig. Structural analysis of the control gear was performed by Universal Technical Systems (UTS). The analysis showed that the gear is on target for handling the applied load.

The primary layout diagram for the test rig is shown in Figure 7. The system is flexible, and hardware changes could easily be made. Actuator response speed was measured using the test rig to simulate increase and decrease of compression ratio. Compression ratio range for the engine will be 18:1 to 8.5:1. Actuator ram travel is ~69.5 mm. Test rig pressure was set at 350 psi. Maximum force on the actuator was ~4893N (1100 lbf). Hydraulic pressure vs. ram displacement was measured using a National Instruments data acquisition (DAQ) module NI USB-6218 and LavView 8.2.

Figure 8 shows measured results representing a reduction of compression ratio. The upper graph Amplitude (Y axis) is hydraulic pressure in psi and the lower graph Amplitude (Y axis) is ram displacement in millimeters. Time is recorded in seconds on the X axis. The graphs show that the hydraulic ram traveled its full stroke in ~0.35 seconds. The graphs also show substantive unsteady pressure in the hydraulic system. Start and stop of the hydraulic cylinder displays sharp pressure vibration. Ram travel commences about 0.05 seconds after the hydraulic solenoid fires. The hydraulic sensor shows a higher initial firing pressure than the available line pressure. The cause of the high initial pressure reading may be due to placement of the hydraulic pressure sensor, where the initial burst of hydraulic fluid jets directly onto the head of the pressure sensor. Mid stroke shows a reduction in line pressure. Improved hydraulic porting would likely improve mid stroke pressure and increase actuator response speed. Accordingly, improved hydraulic ports were designed**.**

Figure 9 shows measured results representing an increase of compression ratio. The graph shows that the hydraulic ram traveled its full stroke in ~0.70 seconds. On average 0.074 seconds is projected to elapse for each point increase in compression ratio. Increase in compression ratio will take about twice as long as reduction in compression ratio.

Referring no to Figures 8 and 9, the pressure graphs show higher mid-stroke pressures when compression ratio is increased than when compression ratio is reduced. The higher mid stroke pressures during increase of compression ratio are due to increased time for hydraulic flow and pressure build-up.

Phase I actuator response exceeded expectations considering the relatively low 350 psi line pressure. The actuator system is also much quieter than expected. An earlier concern was that the actuator would produce a slamming noise when it hit the end of its stroke. Use of hydraulic dampers was planned for. These dampers are not necessary and will not be used.

PHASE 2 DEVELOPMENT

Envera’s earlier 1.8L VCR engine was based on a modified production crankcase. An assumption at the start of Phase 2 was that the VCR mechanism and its actuator system can be manufactured at low cost if these components are integrated into the crankcase. In Phase 2 a new VCR crankcase was developed and optimized using finite element analysis (FEA). The resulting crankcase demonstrates that the VCR mechanism and its actuator can be realized at low cost if the crankcase is designed from the outset to accommodate these parts.

Figure 4 shows the crankcase with integrated VCR mechanism and hydraulic actuator. The optimized hydraulic actuator geometry from Phase 1 is used in the new crankcase. A bedplate is used to support the eccentric crankshaft cradle in the upper crankcase. The crankcase structural design and detailing draws from a current production Honda 4-cylinder engine of similar bedplate construction.

Figure 3 shows the preferred layout of the VCR system. The hydraulic cylinder is located vertically adjacent to cylinder bore 3 to provide a compact and stiff crankcase. The upper crankcase weighs about 20 kg. The crankcase was designed with draft in all directions, for simple low-cost casting. The crankcase was also designed for low-cost machining. All machining operations are at simple right angles except for the oil feed lines down to the eccentric carrier.

A critical element of all crankcase designs is structural stability and stiffness. The Envera crankcase and VCR mechanism were developed using FEA. The FEA was performed using ProEngineer Mechanica software and high-performance quad-core CPU hardware. The crankcase design was strengthened based on FEA modeling results. The eccentric carrier ("crankshaft cradle") provided the desired stiffness without modification, but could be lightened in some places and further stiffened in others.

FEA simulation run time for the crankcase/cylinderhead assembly is approximately 54 hours. Figure 10 shows FEA analysis results. Initial results were excellent. Bottom-end structure is sound and stiff. Minor modifications base on FEA results include the addition of a structural fin below the rear oil drain back gutter to provide more robust head gasket support in this area. Fastener bosses were also enlarged in selected areas. A356 T6 aluminum has been specified for prototype casting. A lower cost aluminum may be used for mass production.

The feasibility assessment of the new crankcase also included production of the machine drawings and tolerance specifications. The machine drawings show that the new crankcase can be mass produced using tolerances and machining operations that are compatible with low-cost mass production.

The new VCR actuator geometry was rig tested in the original Envera 1.8L crankcase. The eccentric crankshaft cradle was assembled in the engine crankcase for the rig testing. The new larger bore (∅50.8 mm) hydraulic cylinder was used to drive the rack of the rack-and-pinion actuator system. Compressed air was used to provide resistive torque on the actuator system. The resistive torque was representational of the torque on the eccentric crankshaft cradle that will be encountered in the firing engine. Rack displacement speed was measured using a National Instruments data acquisition (DAQ) module NI USB-6218, Lab View software and a linear displacement transducer.

The response speed of the actuator system was slower than under Phase 1 testing due to cradle OD bearing friction. Phase 1 testing did not include OD bearing friction. Phase 2 test results indicate that a hydraulic pressure of 520 psi will provide a fast actuator response. VCR actuator response projections are shown in Figure 11.

Actuator power consumption was estimated to be about 400 watts over a duration of about 1 second. During aggressive stop-and-go city driving the actuator may fire twice (up and then down) every few minutes. Assuming the actuator fires twice every 3 minutes, average power consumption will be about 4.5 watts (400w/s x 2/180s). Power consumption of a 2-position VCR actuator system is not expected to have a significant impact on vehicle fuel economy because the average power consumption is small.

Comments and Recommendations

1. More streamlined hydraulic porting will improve VCR actuator response.

2. A slightly larger bore hydraulic cylinder can be used to further reduce hydraulic pressure if needed.

3. The hydraulic actuator is notably quiet in operation.

4. Actuator power consumption is estimated to be about 400 watts with a duration of about 1 second.

5. In future vehicles having 2-position VCR (high and low), actuator power consumption is unlikely to noticeably detract from vehicle fuel economy. *The actuator is used too infrequently and for too short a time to adversely effect vehicle mileage.*

Major Program Accomplishments

1. Design of a low-cost fast-response VCR actuator

   Hydraulic pressure requirements reduce by approximately 75 percent.
   A commercially viable VCR actuator geometry was developed.

2. Design and structural development of VCR crankcase with fully-integrated hydraulic VCR actuator.

   A commercially viable prototype VCR crankcase and VCR actuator were developed.

Technology Transfer Activities

1. Publications:

   The project has been published in the Department of Energy's Office of Vehicle Technologies Advanced Combustion Engine Annual Report in 2006, 2007, 2008 and 2009.

2. Presentations:

   The project has been presented before the Department of Energy's Office of Vehicle Technologies Advanced Combustion Engine Annual Merit Review in 2007, 2008 and 2009.

3. Patents:

   No patents were produced under the program.

Program Support

The development effort described in this report was made possible by the generous support of the National Energy Technology Laboratory and the US Department of Energy. Roland Gravel of the DOE and John Conley of NETL deserve special recognition. Their technical insight and support was central to this program's success. Drew Ronneberg, Gupreet Singh, Ken Howden and Rogelio Sullivan also deserve thanks for their critical review and support of the VCR program, which has proven instrumental to development of a commercially viable VCR mechanism.

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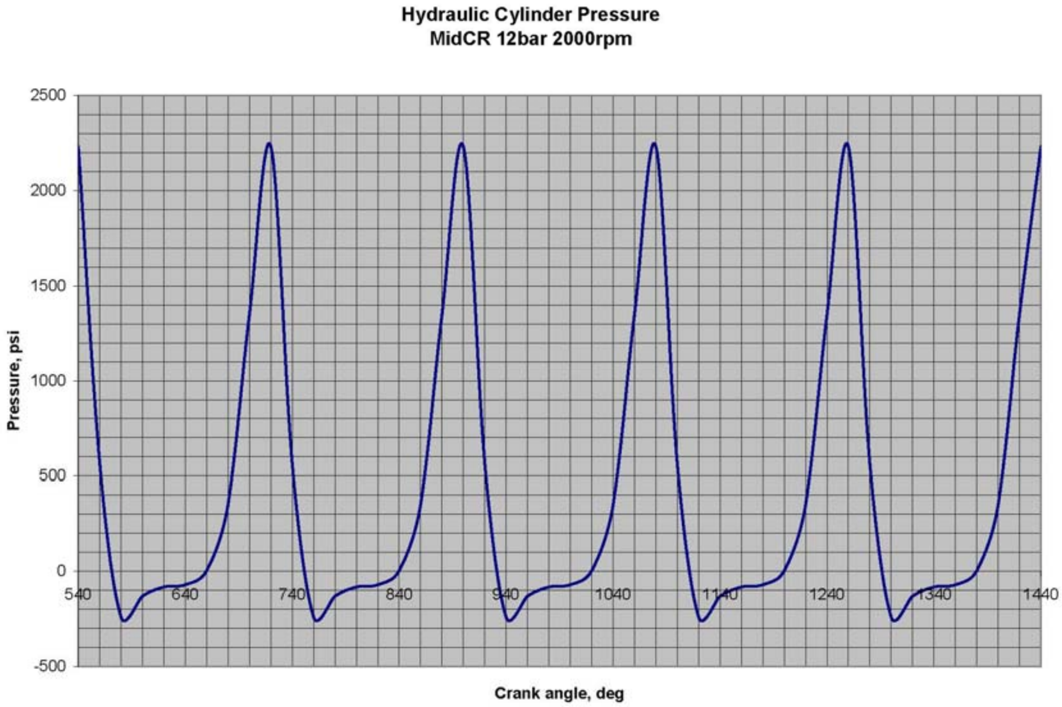


Figure 5 – Base case hydraulic cylinder pressure vs. crank angle at mid compression ratio. Peak hydraulic cylinder pressure is approximately 2250 psi.

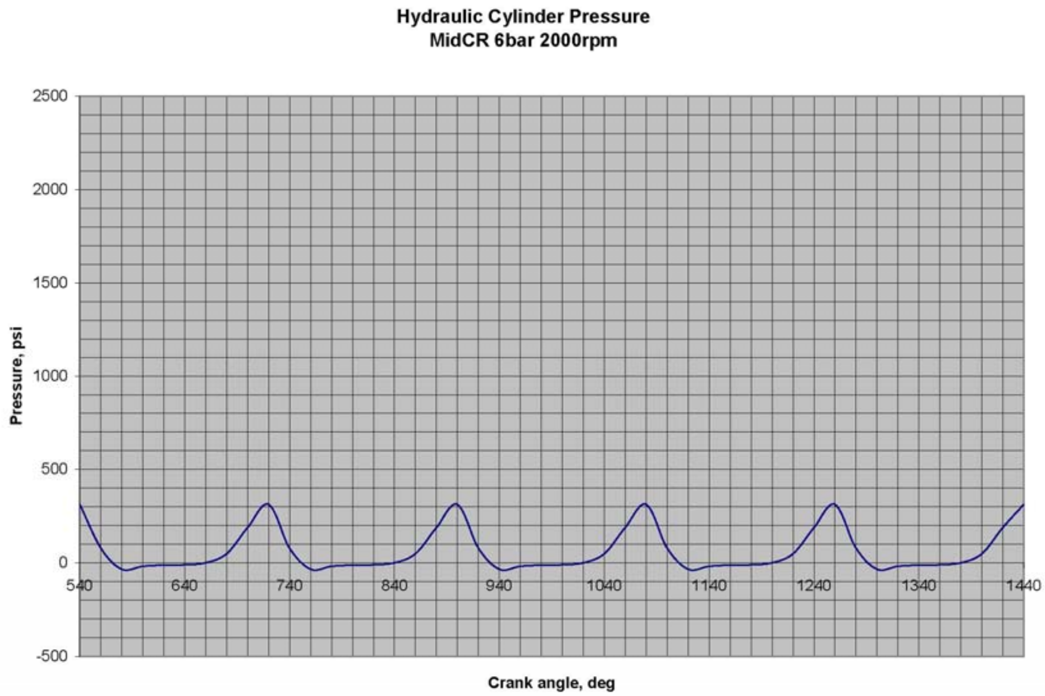
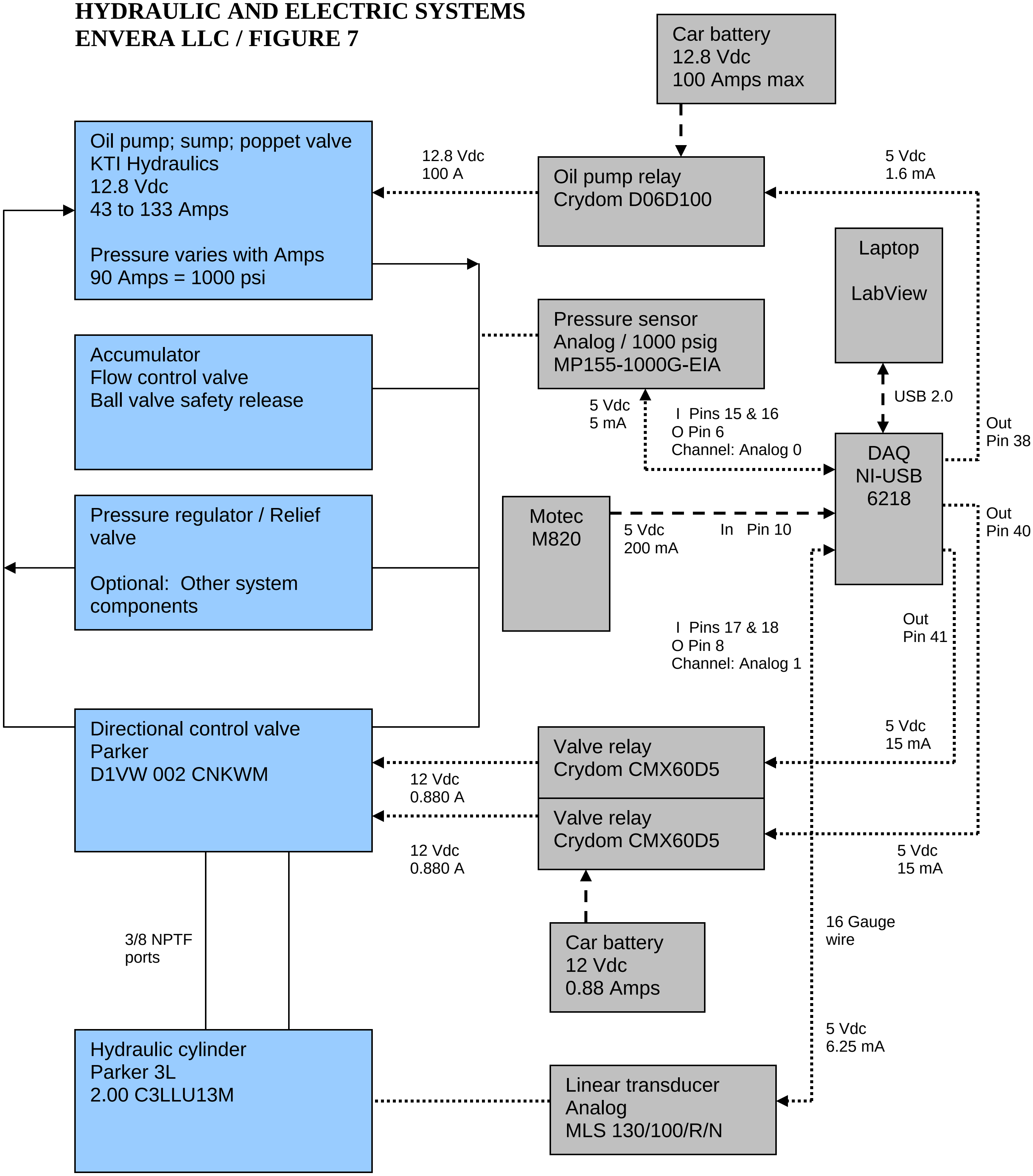
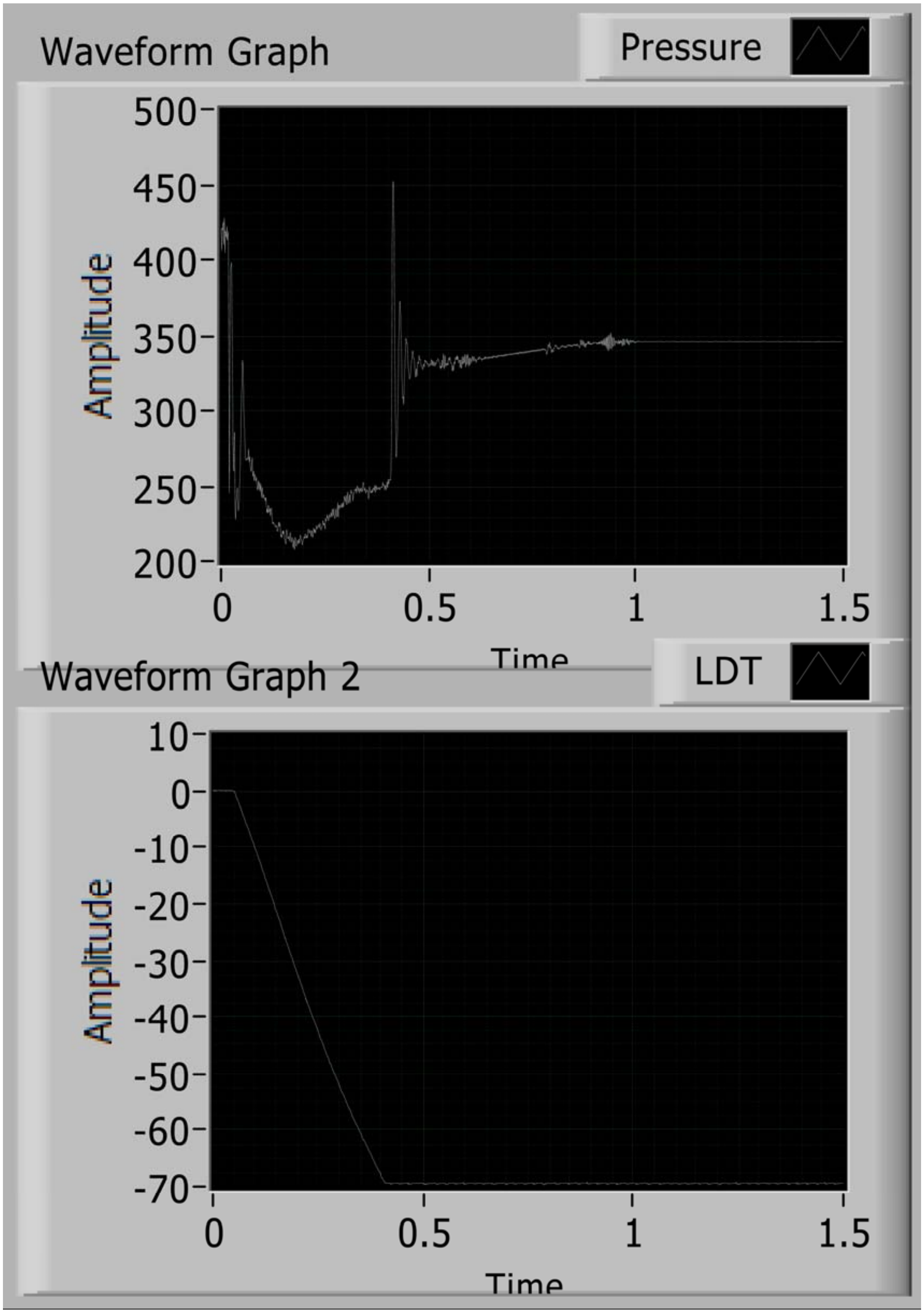


Figure 6 – Optimized system hydraulic cylinder pressure vs. crank angle at mid compression ratio. Peak hydraulic cylinder pressure is approximately 314 psi.

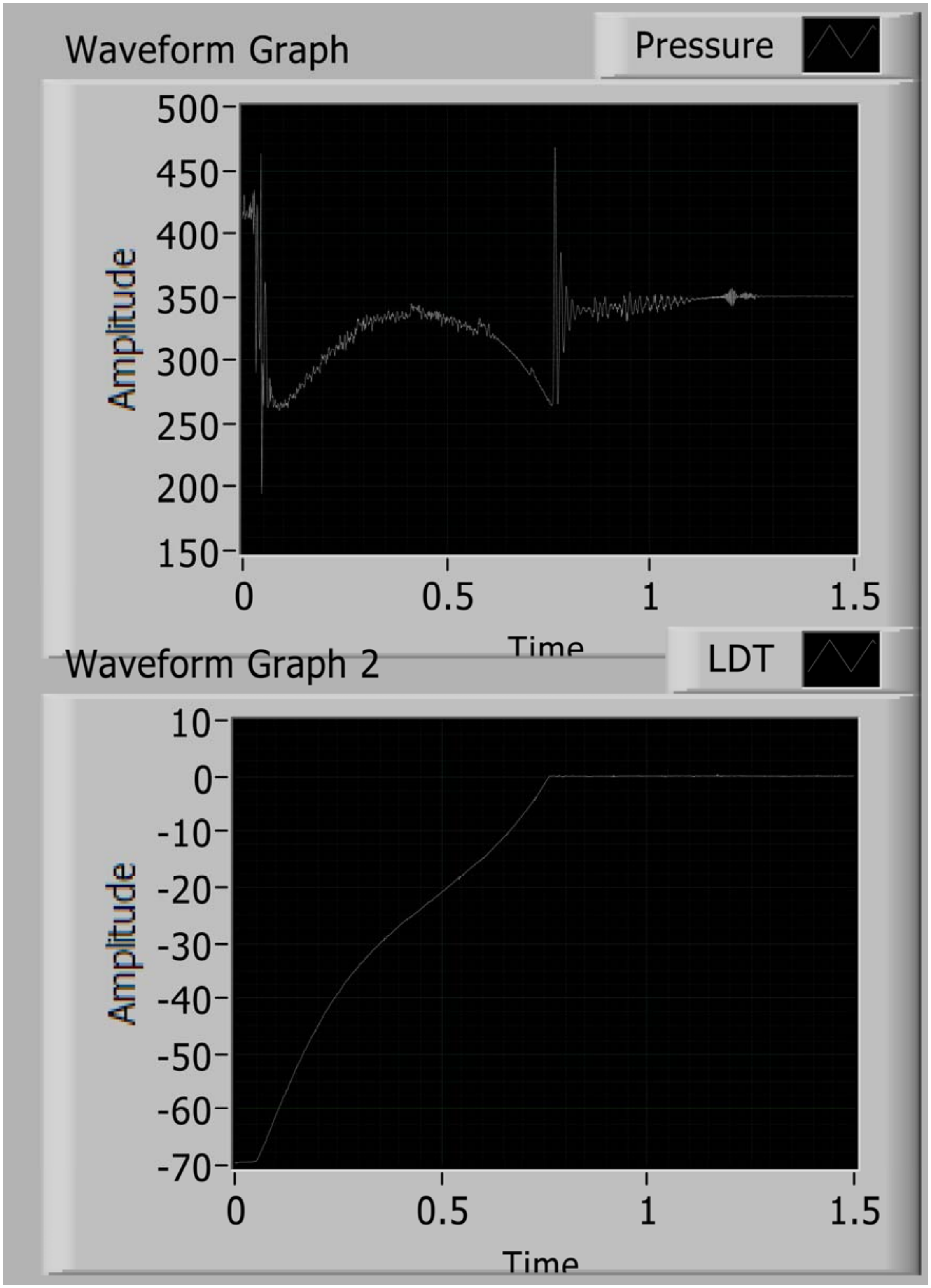
HYDRAULIC AND ELECTRIC SYSTEMS
ENVERA LLC / FIGURE 7



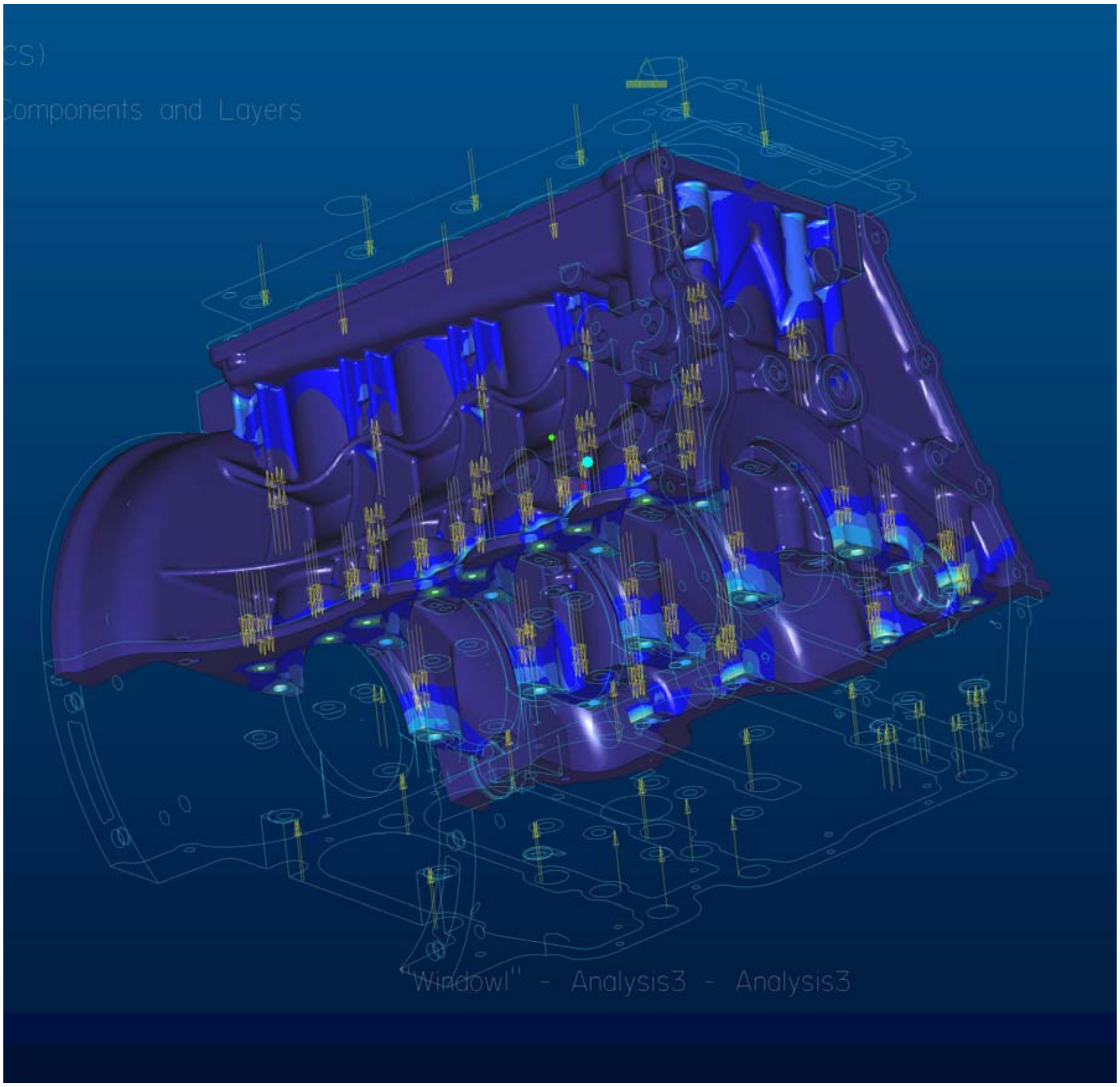
TEST RESULTS FOR REDUCTION OF COMPRESSION RATIO
FIGURE 8



TEST RESULTS FOR INCREASE OF COMPRESSION RATIO
FIGURE 9



FINITE ELEMENT ANALYSIS OF VCR CRANKCASE
FIGURE 10



VCR ACTUATOR RESPONSE PROJECTIONS
FIGURE 11