DESIGN AND IMPLEMENTATION OF A MULTIPLE FUEL INJECTOR DRIP SENSOR TEST STAND

Jason Chekansky  
Project Manager  
Mechanical Engineering

Hugh Campbell  
Lead Engineer  
Mechanical Engineering

Matthew Kubarek  
Mechanical Engineering

Brian Crawford  
Mechanical Engineering

Peter Boyer  
Mechanical Engineering

Richard Peffer III  
Electrical Engineering

Courtney Stout  
Industrial and Systems Engineering

ABSTRACT

The objective of the Fuel Injector Drip Sensor Test Stand team was to design and implement a stand alone fuel injector drip sensing system. The project includes the development of a fuel injector drip sensor, a data acquisition system, and an explosion-proof test chamber. The desired output of the complete system allows for a push button style operation that records the number of fuel drips from each fuel injector during a single test cycle.

INTRODUCTION

Due to the viscous nature of gasoline, fuel accumulates at the injector tips throughout the course of operation. The large mass of fuel eventually falls off when gravitational forces overcome stiction forces within the fuel. These large, unmetered drips are several times the mass of any individual fuel pulse. Engine combustion and emissions are affected by the fuel drips, as the additional fuel introduced to the combustion chamber changes the characteristics of the air-fuel ratio and burn process.

Results from fuel injector drip testing provide data for the analysis of different fuel injector tip styles, and the susceptibility to fuel drip formation. Data is also used to determine if any linearity or non-linearity exists in drip formation.

The current drip detection system in place at Delphi Technical Center, Rochester, NY, is extremely labor intensive. The system is only capable of testing one injector at a time, and requires constant user attention throughout the 10 minute test cycle. The operator is first required to purge air from the fuel lines and remove any fuel from the injector tip. After the test cycle has started, the operator is required to visually monitor the fuel injector tip for drip formation, and eventually distinguish the falling fuel drip from the pulsing fuel vapor. Each time a fuel drip falls from the injector tip, the operator records the time of the drip using an MS-Excel macro routine. This method is both tedious and inefficient, as valuable man-hours are wasted.

The developed drip test stand system needed to incorporate an automated solution to the drip sensing problem. The system would free the operator from constant observation of fuel injector tips, and provide results in a usable form similar to the existing Excel system.

The drip test stand system is also required to test multiple fuel injectors simultaneously through a range of 0°-90°, with the injector axis being completely vertical at 0° and completely horizontal at 90°. This
includes an injector positioning system with pertinent electrical and fuel services capable of the full range of motion. The fuel drip sensor and LabVIEW based data acquisition system would need to distinguish fuel drips from the pulsing fuel vapor, along with the capability of being merged with the existing fuel pulse algorithm. The data acquisition and fuel injector control systems needed to be adaptable to OEM, SAE, and Delphi fuel drip testing procedures.

The explosion-proof, quiescent test enclosure needed to ensure the safety of the operator, as well as allow access to fuel injector and sensor apparatus. To accomplish this, a pressure relief system and accessible front panel needed to be developed. Another key requirement for the test enclosure is the capability to withstand a full vacuum load.

The complete test stand system must also adhere to all relevant safety codes and regulations regarding gasoline vapor control.

**FUEL INJECTOR DRIP SENSOR SYSTEM**

The sensor system is required to detect the presence of a fuel drip and distinguish the drip from fuel vapor spray. The sensor system must then relay the detection of the fuel drip to the data acquisition system in a usable form.

The sensor system is composed of (6) accelerometers, (6) diaphragms, (6) annular clamp rings, (6) base fixtures, (6) accelerometer cables, and (1) signal conditioner. A 100 mV/g accelerometer is securely adhered to the center of a 3.50” (88.9mm) diameter, 0.006” (0.15mm) thick aluminum diaphragm. The diaphragm is clamped at the outer boundary between a 0.25” (6.35mm) tall x 0.216” (5.49mm) thick x 3.50” (88.9mm) outer diameter annular clamp ring and 2.00” (50.8mm) tall hollow cylinder base fixture.

The accelerometer cable is sealed to the top of the accelerometer and routed through the backside of the base fixture. One assembly is positioned 4.00” (101.6mm) below each of the 6 fuel injector tips.

The signal conditioner supplies the accelerometer with a constant 5.0 volts. This provides the reference voltage for drip detection. Upon impact, the falling drip will excite the diaphragm with an impulse force. The acceleration of the diaphragm will be directly transferred to the accelerometer. This will cause a change in the piezo-resistive properties of the accelerometer and return a voltage spike to the signal conditioner.

**Design**

The sensor system is required to detect drips from 6 separate fuel injectors throughout the course of a 10 minute test cycle. To accomplish this, the package needed to be responsive to the fuel drip and capable of detecting multiple drips throughout the test cycle.

The diaphragm is a key component of the sensor outfit. A diaphragm with a large mass and high stiffness would not transfer energy to the accelerometer. If the diaphragm failed to quickly damp the oscillation, a drip may be missed.

Diaphragm material selection was based on characteristics that included response magnitude and decay envelope. Material candidates included high density plastic, low density plastic, and a number of aluminum alloys. Using a mock set-up of the fuel injector test system, experimental work was conducted to collect data and determine the response magnitude and damping ratio. Analytical work was conducted to determine the natural frequency of materials based on geometry and material properties. Decay envelope plots were used to determine the ability of each material to damp a 1 g impulse excitation. 3000 series aluminum with 0.006” (0.15mm) thickness and 3.50” (88.9mm) diameter was selected based on the results. A natural frequency of 1232 rad/s and damping ratio of 0.0459 were determined for the circular aluminum plate.

The aluminum plate was able to provide the required responsiveness as well as damp the unit impulse to less than 3% in 100 milliseconds. This provides the sensor system with the capability to accurately detect up to 10 drips per second.

To address pooling of successive fuel drips on the top of the diaphragm, a 7.5° offset was implemented into the bottom of the base fixture. This allows the fuel to run to the low side of the diaphragm without impeding the impulse force of the subsequent drips. A 0.25” (6.35mm) wide x 0.100” (2.54mm) tall channel milled into the bottom side of the annular clamp-ring.
allows fuel to run off the top of the diaphragm and down the side of the base fixtures.

**DATA ACQUISITION SYSTEM**

The next project requirement is the creation of a LabVIEW interface that would control the 6 fuel injectors and monitor the 6 drip sensors. Therefore, the LabVIEW program was divided into three main sections: fuel injector control, sensor input, and data reporting.

**Fuel Injector Control**

To cycle the fuel injectors, a digital signal is created in LabVIEW with selectable cycle period, injector on-time, and total test time. These values are controlled through the front panel display of the LabVIEW program before the operator begins the test. Due to two types of solenoids being tested at Delphi, a switch is also present to invert the signal sent to the injectors.

To prepare the injectors for testing, a purge cycle is initialized. The separate panel on the program’s display is present for the shorter purge cycle. The operator can enter a different period width, injector on-time, and total cycle duration for the purge cycle. A button is also present to allow the operator to create a constant injector spray. During the purge cycle, the controls for starting the test cycle are disabled to prevent the operator from trying to start the test cycle until the injector purge is complete.

The test cycle has independent controls for the settings of period, injector on-time, and total test duration. To generate a steady and constant output, the LabVIEW program generates a square wave array from zero to one. The frequency and duty cycle are controlled by the values that the operator inputs for period and injector on time. This data array is sent to the digital output control that generates a five-volt pulse via the internal PCI card and external BNC board. Due to the lack of a driver box that will divide the digital signal into six separate 13 volt lines, the program currently uses the existing test program and ISA card to drive the fuel injectors. This card is attached to Delphi’s “Justin” box that has outputs for the fuel injectors.

To address safety concerns, an emergency stop button will be placed on the outside of the system control tower. In the case of a need to immediately turn the system off, the emergency stop will cut power to the complete sensor system. The fuel injectors will return to the closed position at 0 volts, and fuel will no longer be supplied to the test chamber.

**Sensor Input**

The LabVIEW program detects drips using the sensor system input. During system testing, a maximum sensor input of 100 millivolts occurred. This voltage is based on the output sensitivity of the accelerometer. The program reads the accelerometer voltage at a frequency of 1000Hz with an internal memory buffer of 2000 samples.

After a fuel drip excites the sensor system, the program executes a time stamp by changing the case structure loop to a true case as the threshold voltage is exceeded. The current elapsed test time is added to an array of previous time stamps separated by a tab constant. This time stamp array remains unchanged through the utilization of a shift register on the outer while-loop of the program. The array passes directly through the inner case structure loop when the limit has not been exceeded. The program continues to monitor the input signal from the accelerometers until the elapsed test time matches the total test time selected by the operator.

![LabVIEW Operator Interface](image)

**Figure 3: LabVIEW Operator Interface**

The data acquisition system also has the capability to begin monitoring drips after a predetermined test cycle time has elapsed. The system allows the operator to control the delay until drip detection begins. The fuel injectors will cycle during the prescribed delay time and any detected drips will be ignored. During this, the elapsed test time is compared to the delay time and passes a true statement to the stop terminal of the DAQ sub-VI when the delay time has not passed. When delay time is surpassed by elapsed test time, the statement changes to false, informing the DAQ sub-VI to begin monitoring the input signals.

At the bottom of the LabVIEW front panel, a graph of the scaled sensor input versus time is created. This provides a check for the operator to compare the displayed array times to the actual sensor input. The impact of a drip can be seen on screen as a spike in output voltage. The graph can be switched to display each of the six drip sensors.

**Data Reporting**

Information boxes on the front panel of the LabVIEW interface allow the operator to enter data for
the test being performed. Items included are filename, test description, EWO designation, test requestor and operator, fuel type, fuel pressure (kPa), chamber vacuum (kPa), fuel injector orientation angle, and electrical connector position. For each fuel injector, an individual part number and serial number field are available. When the test is completed, the data from these boxes along with the drip time array for each injector are exported to a preformatted Excel sheet. If the test description field or the EWO numbers are left blank, the operator will be prompted for this information before the data is saved under the filename path. The file will be saved in the Excel format. The process of the program is carried out through a sequence structure in LabVIEW and several sub-VI’s supplied by Delphi.

DAQ Hardware

The data acquisition system, or DAQ, is compromised of several different components for the output and input from the LabVIEW program. The output from LabVIEW is currently sent to an internal ISA card in the computer. This ISA card communicates with a driver box known as a “Justin” box. The driver box divides the command signal into separate channels for each fuel injector. These channels are connected to the fuel injectors through wires fed into the test enclosure through rubber stoppers. They are then attached to the fuel injector through a common Delphi supplied plug. This completes the output portion of the DAQ. In the future, the signal from LabVIEW will be sent to the PCI card currently used for input of the accelerometer signals. The digital pulse signal will be relayed to the external BNC board that will produce a zero to five volt TTL signal. This pulse signal will be fed into a driver box that has yet to be manufactured at Delphi. It is assumed that the driver box will have individual switches to enable or disable the output to each fuel injector. From the driver box, the signal will continue to the fuel injector as in the previously described setup.

For the input signal, the voltage source originates in the signal conditioner box. Each accelerometer is attached to a port on the signal conditioner using a coaxial cable. In addition, the signal conditioner also outputs a voltage to the BNC connector board. Each of the six channels occupied by the BNC board relay the voltage from the designated accelerometer. The BNC board is attached to the computer’s internal PCI card through a 68pin cable. LabVIEW amplifies and monitors the voltage from these channels by means of its DAQ Assistant sub-VI.

TEST ENCLOSURE

The design of the test enclosure had to ensure compliance with a number of key requirements. First, the enclosure was designed to be explosion-proof. This is in a sense that, if ignition of fuel were to occur in the test chamber, the top of the enclosure will release internal pressures towards the back of the enclosure to protect the operator. The test enclosure is also capable of withstanding a full vacuum load. This allows for fuel injector testing in an environment similar to an intake manifold setting, as well as evacuation of hazardous fuel vapors. The third requirement of the test enclosure is to incorporate an injector positioning system that would allow drip testing throughout an orientation range of 0°-90°. The enclosure is also required to accommodate all pertinent injector fuel and electrical supplies, data acquisition apparatus, vacuum, and nitrogen purge services.

Enclosure Design

The test enclosure is constructed from 0.5” (12.7mm) thick 6061 aluminum walls that are welded at the seams. The walls are reinforced with 1.00” (25.4mm) square 6061 aluminum tubing with 0.125” (3.175mm) wall thickness. The center span is reinforced with a 0.5” (12.7mm) thick 6061 aluminum load bearing plate positioned at the center of the enclosure. The reinforcements were made to ensure that the enclosure is capable of withstanding the high external pressures associated with vacuum loading.

A finite element analysis was performed on the test enclosure to determine structural stresses. A full vacuum load was simulated using COSMOS FEA software. The analysis was performed to ensure that the enclosure was capable of withstanding vacuum load and the appropriate material and thickness was selected in the most cost efficient means. The enclosure design provided a factor of safety of 2, with negligible displacements at the top panel and back wall. A full vacuum load is capable based on results from the FE analysis. The small displacements seen ensure that sealing of the top plate and front panel is accomplished.

The removable front panel provides the operator with full access to the test chamber. This design also allows for quick and simple set-up. During testing, the front panel is affixed to the test enclosure using Steco clamps. Vacuum sealing is achieved using a large O-ring that is adhered to a recess in the panel. A polycarbonate viewing window allows the operator to monitor drip testing.
Injector Positioning System

The injector positioning system utilizes (2) fuel injector fixtures. Each fixture, mounted on separate sides of the center wall, holds (3) fuel injectors, (3) fuel injector adapters, (3) sets of fuel supplies/electrical services, and a locking system to hold the injector fixture at the desired orientation.

Orientation changes are supported by a spring loaded locking system that allows changes to be made in 5° increments. The orientation change is made by pulling the pin from the locking plate and rotating the injector positioning fixture to the desired angle. The pin releases into the correct dial plate hole and locks the system at the desired orientation.

To keep set-up time at a minimum, the injector positioning system was designed to place the fuel injector tip at the same point for all injectors. This requires no repositioning of the sensor assemblies for each injector. To accommodate 80% of Delphi fuel injectors, an adapter system was developed. The adapters are threaded into the top plate of the positioning system. Fuel services are connected at the top of the adapter. The injectors are mounted to the opposite end of each adapter using the same clip-style technology that is used to affix the injector to the fuel rail in vehicle applications.

CONCLUSION

The fuel injector drip sensor test stand system provides an automated solution to the unique problem of sensing fuel drips. The drip sensor system operates without constant user attention, and data output is recorded in usable form as a MS-Excel workbook. Multiple injectors can be simultaneously tested through a 90° range of orientations. The explosion proof test enclosure is capable of withstanding full vacuum loads and allows complete access to the test chamber for ease of set-up.

The operator is also provided with a number of procedural documents. This includes a Failure Mode and Effect Analysis for the sensor system, data acquisition system, and test enclosure. Maintenance documents are also provided for the sensor system for repair procedures as well as yearly accelerometer calibration.

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