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RIT Formula SAE Dynamometer Test Facility

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ABSTRACT

The Rochester Institute of Technology Formula SAE Racing Team is a group of approximately twenty students dedicated to the design, fabrication, racing, and promotion of a high performance formula-style racecar. The all-volunteer team is responsible for every aspect of the project including engineering, design, financial management, and public relations. Each year the team builds an entirely new racecar with restrictions only to the car's frame and engine to challenge the students' knowledge, creativity, and imagination. RIT competes among a field of over 130 universities, and is judged on the vehicle's design, cost, and performance, as well as the team's ability to present the engineering concepts used in the final design.

The purpose of this project was to design and assemble an engine dynamometer to be used by the RIT Department of Mechanical Engineering and the RIT Formula SAE Racing Team. Useful engine data is recorded and processed using National Instruments hardware and software. Design emphasis was placed on sub-system compatibility, ease of operation, and overall robust design and reliability.

INTRODUCTION

A dynamometer is a device that measures mechanical force, speed, or power. An engine dynamometer places a load on an internal combustion engine and measures the amount of power that the engine can produce against the load. The two main types are chassis dynamometers and engine dynamometers. Chassis dynamometers involve using an entire vehicle and measuring torque and speed at the wheels, while engine dynamometers measure the power directly at the engine. Our project's focus was primarily on the engine type due to size, cost, and facility considerations. Traditionally, in a dynamometer test cell the drive shaft of the internal combustion engine is mated to the dynamometer using couplings. When the engine is running, the dynamometer exerts a braking force on the engine and at the same time sensors are used to measure engine speed and torque. By using these values the power output of the engine can be determined. An important feature of a dynamometer is its ability to maintain a desired speed or torque for testing purposes, then allowing the power output at that speed to be measured. The most important use for a dynamometer is to be able to tune an engine. Various design changes and modifications can be made to an engine and subsystems to affect its performance. The results can be measured using a dynamometer and all the important temperatures, pressures and other parameters can be monitored and logged to analyze engine performance.

NOMENCLATURE

AC – Alternating Current
AN – Army/Navy
CFM – Cubic Feet per Minute
DAQ – Data Acquisition
DC – Direct Current
DIN – Deutsches Institut für Normung
DIP – Dual Inline Package
ECU – Engine Control Unit
FS – Full Scale
FSAE – Formula SAE
GmbH – Gesellschaft mit beschränkten Haftung
GUI – Graphical User Interface
HP - Horsepower
MAP – Manifold Absolute Pressure
OEM – Original Equipment Manufacturer
PCI – Peripheral Component Interconnect
RIT – Rochester Institute of Technology
RPM – Revolutions per Minute
RTD – Resistance Temperature Detector
SAE – Society of Automotive Engineers

DC Motor

The dynamometer uses a DC motor to place a mechanical load on the Formula SAE team's CBR 600 motorcycle engine. Current power output of this engine is 76 peak HP. The dynamometer is designed with a power handling capacity of 120 HP to account for possible increases in engine power output. The motor we chose to implement was built in Germany by Siemens Automation and Drives. Siemens donated a brand new motor that we chose from their catalog. The motor has a 470 V armature and a torque rating of 795 Nm with an efficiency of 86%.

The DC motor is controlled by a Dyne Systems DynLoc IV dynamometer controller. The controller manages all aspects of motor function during dynamometer operation through closed loop control using RPM and torque feedback values.

The motor is trunnion mounted, which means it is suspended from the drive shafts that protrude from both ends. We specifically ordered the motor to have a shaft protruding from both ends of the motor for this purpose. This method of securing the motor leaves the motor case free to rotate and apply measurable torque to a load cell mounted on the motor's case. This load cell then provides feedback to the Dyn-Loc controller.

The remaining DC power components condition and supply electrical power from the building power supply into the form necessary to power the DC motor. These components are listed below.

An Olsun 3 Phase 460VAC Isolation Transformer isolates the dynamometer from dangerous voltage spikes in the building's power supply and also performs 3-phase AC delta to wye power conversion. Delta and wye are different configurations of 3 phase AC voltages.

An SIEI Typact TPD32-500/520-280-4B DC Drive converts the 3-phase AC voltage supplied by the isolation transformer into the DC voltage necessary to provide power for the DC motor. Several sets of physical disconnects are also part of the system to provide a layer of physical safety and facilitate maintenance.

The following devices will provide a fully functional basic dynamometer system: A DC motor to provide load for the engine under test, closed loop controller to manage dynamometer state, DC drive and AC isolation transformer to provide and regenerate the necessary electrical power.

Data Acquisition

The data acquisition system implemented on the dynamometer is a professional, modern system providing both Formula SAE and the Mechanical Engineering Department at RIT with the capabilities necessary for engine tuning, education, and independent research.

The sensor requirements for this project were determined by soliciting faculty and Formula SAE members, as well as relying on the team's best judgment. Parameters monitored and logged on the dynamometer are:

- Cylinder Pressure
- Fuel Pressure
- Oil Pressure
- Manifold Absolute Pressure (MAP)
- Air / Fuel Ratio
- Exhaust Gas Temperature
- Intake Air Temperature
- Radiator Inlet and Outlet Water Temperature
- Radiator Inlet and Outlet Air Temperature
- Oil Temperature
- Mass Air Flow
- Crankshaft Position and Speed

In addition to the engine parameters acquired, the essential function of the dynamometer requires measurements of:

- DC Motor Speed
- DC Motor Load Torque

The systems hardware requirements are supplemented by using products from National Instruments. The adaptability and excellence of these components provides the professional quality that was demanded by this project. The DAQ card that is used is a PCI-6034E which features a 200 kHz sample rate, 16 single-ended / 8 differential analog inputs and 8 digital I/O's (DIO). This unit is connected to an

SCXI-1001 chassis, which houses and powers the other input modules. The Mechanical Engineering Department was the primary source of sponsorship in this area with their donating of a full system of hardware to interface with all the necessary sensors.

Cylinder pressure measurements are made using charge type pressure transducers from PCB Piezotronics. The 112B10 combustion sensors that were selected utilize an adaptor integral to the spark plug for easy mounting to any CBR600 engine. A National Instruments SCXI-1531 Accelerometer Input Module is used along with charge amplifiers from PCB to meet the necessary signal conditioning requirements of these sensors.

Fuel and oil pressure measurements are taken using strain gage type pressure transducers from Omegadyne. The units that were selected have built in signal conditioning for a 0-10Vdc output, operate on unregulated 24Vdc, and have an accuracy of ±0.25% FS. A 0-100 psig range is used for fuel pressure while the oil pressure measurement utilizes a 0-150 psig range.

Pressure measurements in the intake manifold are made using a Bosch PSC-A MAP sensor. This is an OEM type piezoresistive strain gage transducer that provides measurements from 3 to 15 psia with a standard 0-5Vdc output.

Measurements for air/fuel ratio are sampled using a Bosch LSU-4 Lambda Sensor (Wide-band O_2), which is also used by the Motec ECU for closed-loop fuel compensation. The 0-5Vdc output of this sensor is wired to a differential voltage channel of the DAQ card.

Temperature data is acquired using thermocouples from Omega. Most measurements are made using sheathed K-types with an ungrounded junction. The exception is the intake air temperature measurement, which requires a higher degree of accuracy. This measurement is made using an exposed, ungrounded junction T-type thermocouple. Signal conditioning and cold-junction compensation are handled by National Instruments hardware, mainly a TC-2095 Terminal Block and SCXI-1102 Thermocouple Input Module with multiplexing.

Mass airflow is measured using a Delphi constant temperature hot-wire anemometer. To ensure consistent data, a special pre-manifold intake system was fabricated to provide the proper flow conditions for this anemometer.

To monitor engine speed and position and to trigger the cylinder pressure measurements, an encoder from BEI Industrial Encoders was implemented. The model used is a H25 incremental optical encoder with a minimum increment of ¼° and maximum speed of 12,000 RPM.

To calculate the power output of the engine, both torque and speed of the DC motor are measured. To obtain torque, a load cell is coupled to a torque arm attached to the DC motor. The load cell used is an Interface SM-500, which features a 3mV/V output and 500 lb capacity. The load cell is connected to the dynamometer controller, which provides excitation voltage and signal conditioning. Speed measurements are made using a hall-effect type sensor and a 60-tooth gear mounted to DC motor's output shaft. This sensor also interfaces directly with the Dyn-Loc dynamometer controller. Both torque and speed measurements are used in conjunction to control load and speed of the DC motor via Dyn-Loc Controller. The analog output from both of these sensors is coupled to the DAQ system via a BNC-2095 Terminal Block and SCXI-1104 Multiplexer Input Module to provide a graphical display of power and torque.

Engine Mechanicals

The cooling of the internal combustion engine is achieved through methods used in all modern day vehicles. The main components include a traditional automotive radiator, water pump, and cooling fan. Rubber hoses connect the engine directly to the radiator, and the intake line takes the hot water from the engine and runs it through the radiator. After the cooled fluid exits the radiator it runs through a line that returns it back to the engine. Ball valves are included in the lines to stop the flow of water if the engine is removed. Rubber lines are used and clamped at the connections, which minimizes the time needed to remove and replace an engine. The water pump in conjunction with the thermostat controls the fluid motion through the whole system. Water is used with no anti-freeze in the system because FSAE race teams competing at events are required to use only water in their vehicle cooling systems for environmental reasons. Therefore, our dynamometer system follows those requirements to develop accurate data so that there is no difference from competition and testing.

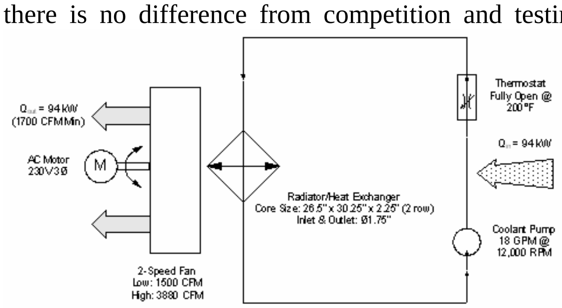


Figure 1: Cooling System

One of the major hurdles for the project was that the previous water brake dynamometer used by the formula team didn't have the capacity to properly cool the engine during subsequent dyno runs. The radiator that was selected for the project is made by Ready-Rad Part # 431390. This radiator is typically installed in the Ford F-series truck with the 7.3L turbo Diesel. The reason that the radiator is so oversized is to provide the proper cooling for the engine. During the dyno runs, an excessive amount to heat is generated and released via the cooling water. In order to provide the proper amount of reserve cooling for extensive runs, the largest radiator within our budget of $300.00 was selected. One main part of the cooling system is the air that is needed to cool the hot water leaving the engine. In order to achieve this we used the existing water brake dyno that the formula team uses and hooked it up a water-cooled heat exchanger to control the water temperature flowing back into the engine. After a few slight modifications to the current system the water temperature flowing back into the engine was 20° cooler that when it entered the heat exchanger. After a few dyno runs it was determined that a delta of 20° would be sufficient to properly cool the engine for continuous dyno runs without introducing a thermal shock to the engine parts or overheating. Once a 20° delta difference was determined it was calculated that the airflow through the radiator needed to be at least 1689CFM. The fan that is mounted to the radiator to simulate a motor driven fan is a 120V is a single speed wall exhaust fan. At low speed the fan provides 6700CFM. This will provide adequate cooling for the engine during all testing procedures and at all RPM ranges.

Special consideration was given to this section to guarantee that the removal of the exhaust gases does not affect engine performance. The main components of this system include a vacuum pump, hose, nozzle, and muffler. The FSAE designed muffler is attached to the Honda engine. The engine creates a large amount of noise that is subdued mostly by the enclosed room, but the muffler reduces the noise even further. We intended to reduce the noise so that it does not distract anyone in the college of engineering when testing is conducted. Following the muffler, the exhaust gases enter a nozzle that will increase the velocity of the air from approximately 600FPM at the inlet to 1500FPM at the Plymovent connection. The nozzle is not directly connected to the muffler but instead is suspended above it.

Figure 2: Plymovent Exhaust Evacuation System

The Plymovent has the capability of actually pulling air through the engine and affecting performance. In order to not increase the volumetric efficiency of the engine while exhausting the gases out of the room, a nozzle was designed for the end of the Plymovent hose. The nozzle increases the air speed from 676FPM at the inlet to 1521FPM at the outlet. A series of 2 readily available HVAC increasers were used in the design. The nozzle is 4 inches on the hose side and 12 inches at the end open to ambient air. Figure 3 shows a drawing of the nozzle.

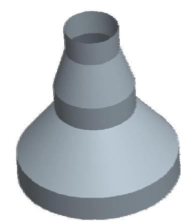


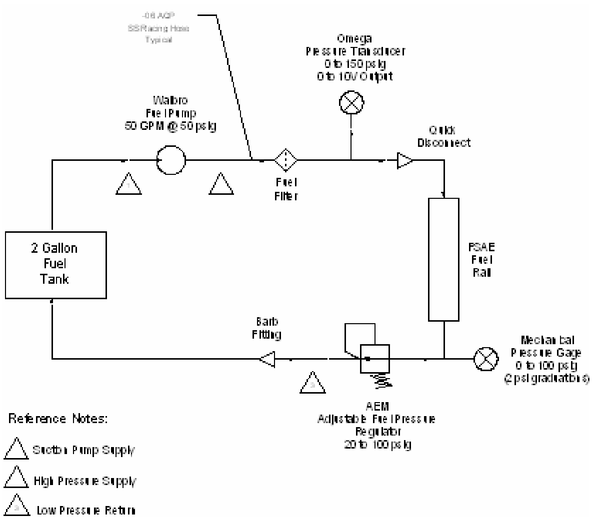
Figure 3: Exhaust Nozzle

The other end of this Nozzle attaches to the vacuum device manufactured by Plymovent. It pulls the exhaust gases from the room to the outside of the building. The Plymovent system has a hose that is retractable so it can be attached to the nozzle during testing and recoiled out of the way when not in use. Calculations were performed to determine the size of the nozzle required to bring the velocity of the exhaust gas leaving the muffler to nearly 0mph.

Finally, combustion of fuel in an engine creates harmful gases so a carbon monoxide sensor is installed in the room for precaution. The FSAE team already is in possession of one and uses it with the current system.

The fuel system consists of a fuel tank, fuel pump, filter pressure regulator, mechanical pressure gage, and fuel rail. It is a closed system in which unused fuel passes through the fuel rail and returns to the fuel tank. Please refer to Figure 3 for the fuel flow diagram.

Figure 3: Fuel Flow Diagram



The fuel tank that is used was left in the test cell and was originally used with a Ricardo engine. It is mounted to the frame of the dyno for easy access. A braided stainless steel fuel line made by Aeroquip is used throughout the system as well as Aeroquip fittings for the high-pressure lines. A line runs from the fuel tank to the fuel pump, which is powered by 12VDC from the dyno controller. A line runs from the fuel pump to the fuel pressure regulator and then to a fuel pressure gauge. This gauge confirms the setting on the regulator and is used as a visual indicator. Following this, a line runs to the fuel rail, which is designed by the Formula SAE team. A line runs from the end of the fuel rail back to the fuel tank and returns any unused fuel that did not go through the fuel injection system. Quick disconnects are used on the fuel lines for easy set-up and teardown and the connection points are mounted to the frame of the dynamometer.

Engine Management

An adaptable and flexible engine management system is the center of any modern engine test stand. In addition to the advantages that fuel injection has for performance, economy and emissions in today's engines, it creates a simple way to test and tune engines before being installed in their appropriate applications.

The project utilizes the Motec M400 engine management system to control fuel and ignition on the engine. Fuel is metered into each individual engine port by sequential fuel injectors. The injector is controlled by adjusting the pulse-width of the electromagnet which actuates the pintle valve. This pulse width is determined by the injector flow rate, fuel pressure, and volumetric efficiency of the engine at a particular engine speed. These various pulse widths are recorded for a variety of engine speeds and loads to create the engine fuel map. Other parameters are used to adjust the fuel map including air and engine temperatures, transient throttle position, and closed-loop oxygen sensor control.

The ignition system is comprised of two dual-ended coils in a wasted spark configuration. On a four cylinder engine, one double-ended coil will fire two cylinders, one on the power stroke, and the other on the exhaust stroke. The spark moment on the exhaust stroke is what is referred to as the wasted spark. This system allows the elimination of two ignition outputs and 2 extra coils. Ignition timing is also controlled using the Motec engine management system. An ignition map is created by monitoring engine detonation throughout a range of engine speeds and loads similar to the fuel map. The engine controller then sends ignition signal to the power stage at the specified crankshaft angle. Parameters used to adjust and modify this angle are engine detonation monitored by a knock sensor and ignition delay time which is used to compensate for the delay of different ignition coils, power stages, and wiring. A picture of the Motec wiring is found below.

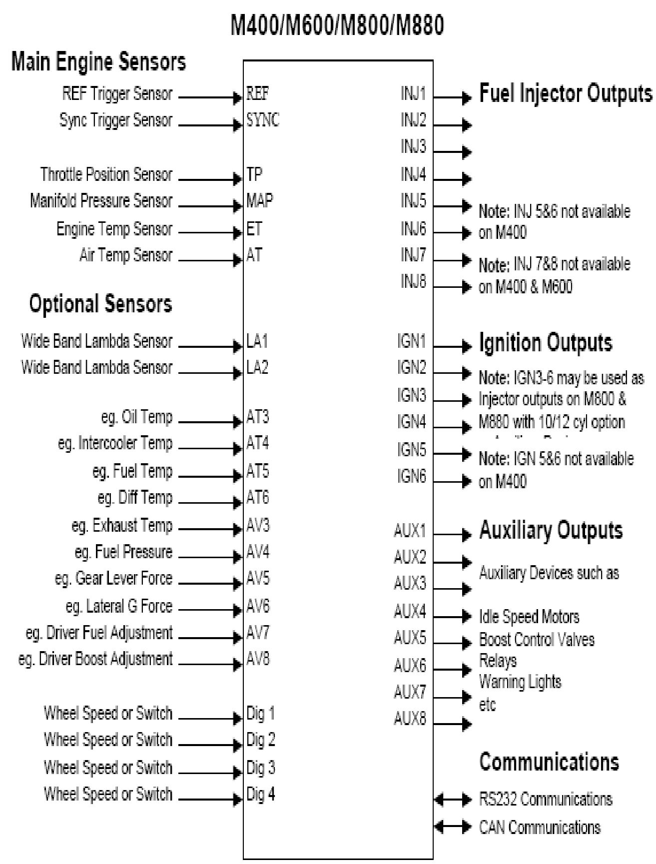


Figure 6: Motec Wiring Diagram

Power Transmission/Chassis

Power transfer between the Honda CBR600 engine and the DC motor is accomplished with a chain drive, similar to that used on the Honda motorcycle. The chain acts as a damper and absorbs the shock caused by fluctuations in the engine's power strokes so not to fatigue the crankshaft. The chain drive was designed with a reduction ratio of 2.50 in order to decrease the output speed of the engine to an acceptable range for the DC motor.

The dynamometer's base is designed to support the loads of the engine and DC motor, for easy access to the engine for maintenance and to be reasonably compact. The DC motor weighs a total of 1345 pounds, and the engine weighs approximately 150 pounds. The frame is constructed of A36 2" square tubing with wall thickness of ¼". Finite Element Analysis was run using ProMechanica, which calculated a maximum deflection of the frame to be 0.009" with a maximum stress of 15,530 psi. The maximum stress occurred at the mounting point of the frame's feet. Figure 4 shows a CAD model of the dynamometer chassis.

Figure 4: Chassis Model

An engine cradle was built specifically for the Honda CBR 600 motorcycle engine. The cradle picks up four of the six stock mounting points on the engine and is attached to the dynamometer frame with four mounting bolts. This setup was chosen because it allows for other engines to be adapted to the dynamometer with only a new cradle necessary to fit the mounting point of the new engine. The engine bolts down to a steel plate, which has a pattern of tapped holes in it allowing for flexibility in mounting various components to the dynamometer such as exhaust brackets. Vibration absorbing/leveling feet are used on the frame to try to absorb some vibration so not to be put into the test cell's floor.

The Siemens DC motor is trunnion mounted along its shaft. The motor has a dual ended armature and there are bearings on each end of the motor for support as described in more detail above. The bearings use a clutch-locking mechanism on the motor's shaft to make sure the shaft does not spin in the bearing. The case of the motor would be able to spin freely on these bearings if not for the lever arm and load cell, which is placed between the lever arm and the frame. The load cell is used to back calculate torque output of the engine through the torque absorbed by the motor. The controls receive the reading of torque output from this calibrated load cell. The load cell and the lever arm are packaged under the dynamometer to protect them. Since the load cell must be calibrated in tension, a cable/pulley system was designed to be able to calibrate the load cell using hanging weights. A diagram

Dynamometer Control and Interface (GUI)

Dynamometer control is performed by a Windows XP PC-based application coded in National Instruments' LabVIEW programming language. This application accomplishes every part of a dynamometer test run except physically starting the engine. In order to do this, the GUI integrates control of the DynLoc controller, the engine throttle, clutch, and the National Instruments DAQ hardware. The GUI can operate in two main modes: manual and automatic. Automatic mode consists of two sub modes, which are regular dyno run mode and a calibration mode for the ECU.

Control of the DynLoc is accomplished through serial communication between the RS-232 ports of the DynLoc and the PC. By communicating with the DynLoc the GUI can control all aspects of the DC motor operation, including rpm or torque setpoints and the rate of change when transitioning from one setpoint to another. A simple library of LabVIEW functions was created so that a LabVIEW programmer can control the DynLoc even with no understanding of the DynLoc's native ASCII command format. This will simplify any maintenance or upgrades that the FSAE team or ME department may wish to perform on the GUI in the future.

A single-acting pneumatic cylinder powered by shop air actuates the clutch. The GUI controls the cylinder with a DIO line which is connected to a solid state relay to step up the control voltage from 5v to 12v before being connected to a solenoid operated valve to direct airflow to the cylinder. This system disengages the clutch with the cylinder and relies on the clutch's internal spring force to return the clutch when air pressure is removed from the cylinder.

The throttle is actuated by an electric stepper motor with 200 steps per revolution, 21 Ohms per coil and 12v input voltage. The stepper motor is controlled by an Allegro UNC5804B Unipolar Stepper Motor Driver/Translator IC, which includes integrated power transistors to drive the motor. This IC is capable of driving 1.25A per phase, well above the 0.6A per phase required by the stepper motor in use. The GUI controls the throttle by providing 2 control signals to the UNC5804B: the direction and step input controls. The direction control signal is provided by a DIO line from the 6034E card. The step input tells the UNC5804B when to move the motor; the motor is moved one step every time a falling edge occurs at the step input control. Control of this input is provided by sending pulses from a counter output on the 6034E card.

Physical controls of the clutch and throttle exist to that the engine can be controlled with no inputs from the computer if desired. Also, a separate physical emergency shutdown button is available in case the GUI loses control of the dynamometer.

The data acquisition is handled by the National Instruments hardware as discussed earlier. The GUI displays the acquired data for the user to see, and saves all the data to spreadsheet files for manipulation and review after the test is complete. There are two output files: one file for the cylinder pressure data and one file for all the other data. This is because of the different sampling rates of the data; cylinder pressure data is taken at predetermined RPM points, and each cylinder has one pressure measurement taken every degree. For one full cycle (two revolutions), 2880 measurements are taken. While this is good for measuring the cylinder pressure, this data sampling rate far exceeds what is needed for the other sensors. Data manipulation is made simpler by writing the data to two files so that the data format does not change within a file.

When the program is started, the user is given the option of entering manual mode or running an automated test. Instrumentation data can be logged from the manual mode if needed, but all the throttle and DYN-LOC set points must be controlled manually. When the user quits manual mode, the program returns to the start point. If an automated test is selected, the program runs the test and returns to the start point when finished. A picture of the GUI is below.

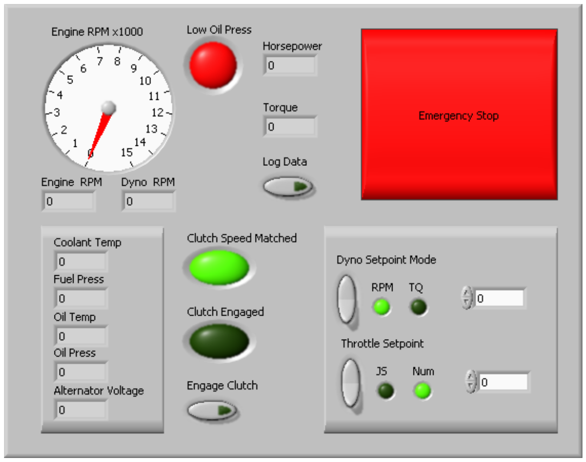


Figure 5 GUI Front Panel

Manual mode gives the user complete control over the dynamometer. This is handy for any use not covered by the auto mode, such as using the DC motor to provide a moderate load to bring a cold engine to its normal operating temperature faster than simply letting it idle.

The first automatic mode test is a normal dyno run. The user specifies the initial and final RPM, the desired rate of RPM change, and the throttle position. The user can also specify RPM points at which to obtain cylinder pressure data. The program then synchronizes the transmission output speed to the DC motor input speed and engages the clutch. Once the clutch is engaged, the throttle is opened to the desired position while the dyno is set to the initial RPM point. After obtaining the desired RPM and throttle positions, data logging begins and the dyno ramps to the final RPM set point, logging cylinder pressure data at the appropriate points along the way. Upon reaching the final RPM, data logging stops and the dyno is returned to its idle RPM as the throttle is closed. At that point the clutch is disengaged and the DC motor is stopped, and the GUI returns to its initial state of asking the user to choose manual or auto mode.

The other automatic mode is an auto-tuning mode for the ECU. No data is logged to spreadsheet files in this mode. Its only purpose is to provide the proper conditions for the ECU to calibrate itself. The basic principle of this mode is that the engine steps through several RPM points, and for each RPM point it steps through several throttle set points. The dyno waits for the ECU to calibrate itself at each set point before moving to the next. Once the ECU has been calibrated for each point, the test is over and the GUI returns to its initial state.

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