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Strain Gage Based Instrumentation for In-Situ Diesel Fuel Injection System Diagnostics

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ABSTRACT

Dynamic start of injection (SOI) is identified as one of the key injection parameters that needs to be measured during engine operation in order to study ignition delay and its impact on the qualitative and quantitative aspects of the combustion process in the direct injection diesel engine. Application of traditional SOI measurement techniques, based on needle lift sensors, to unit injection systems presents challenges. Hence, a strain gage measurement technique which is readily available to engineering students and researchers has been adopted to determine SOI for unit injection systems. A strain gage was installed on the rocker arm acting on the unit-injector plunger, and the injection pressure was calculated from the force and the diameter of the plunger. Start of injection was determined from the profile of the injection pressure as a function of crank angle, and the known injector opening pressure. A series of tests was performed on a heavy-duty turbocharged diesel engine, and measurements from 20 consecutive cycles were statistically analyzed. Very small cycle-to-cycle variations in the SOI determined from the injection pressure signal indicate that the strain gage technique is reliable and suitable for rigorous combustion analysis.

INTRODUCTION

The turbocharged direct injection diesel engine dominates the heavy-duty truck engine market as the most efficient powerplant available today. The ever more stringent emission standards have prompted the development of high pressure injection systems and associated electronic controls in order to reduce the amount of particulates and nitric oxide in the exhaust [1]. Electronic injection systems not only give the designer much more control over the combustion process, but also require the use of novel diagnostic techniques in the context of mixing and combustion studies. Such experimental investigations often require a multi-disciplinary approach and therefore have very high educational value for participating engineering students. The tasks include: identification of the parameters that need to be measured for the particular study, identification of signals that will allow indirect measurements of parameters that are difficult or impossible to measure directly; and finally development of post-processing routines that will extract the relevant information from the raw measurements.

Special consideration needs to be given to the fact that the instrumentation will operate in the harsh environment inside an engine.

The key injection parameter needed for mixing and combustion studies is the actual dynamic start of injection (SOI), when fuel first enters the cylinder. Not only does this vary widely with speed and load in modern electronic injection systems, but it also depends on complicated injection line dynamics that make it hard to extract SOI from a simple interrogation of the electronic signal. The injection system investigated here is based on the unit injector design which makes it difficult to instrument directly the injector for needle lift measurement. On the other hand, techniques for force measurement using strain-gages, which are readily available to students and researchers in Mechanical Engineering Departments, could be used to determine SOI. In fact, Henein and Rozanski [8] attempted to use the strain-gage based technique to measure the injection pressure on the rig, outside the engine, in order to evaluate whether it could be used for detection of injection system malfunctions in the field. Their diagnostic methodology was based on the peak pressure value, but the fidelity of the pressure profile as a function of crank angle was not emphasized. Nevertheless, their initial results have provided our team with motivation to develop instrumentation for indirect measurement of the injection pressure in a running engine by measuring the force on the rocker arm acting on the plunger inside the pump element. From these measurements, SOI can be subsequently determined using the nominal injector opening pressure.

The material presented in this paper is arranged as follows: first, the main features of diesel mixing and combustion are reviewed so as to highlight the parameters that need to be determined in order to characterize the phases of combustion. The design of the system based on the unit-injector with an electronically-controlled spill valve is examined next. This is followed by the description of the instrumentation developed to measure the force on the rocker arm. The experimental set-up for testing of a heavy-duty automotive diesel engine, fully instrumented for cycle analysis and in-situ injection diagnostics, is subsequently described. Next, signal conditioning and the detection of SOI from the rocker arm force signal are described together with sample results. The work is summarized and conclusions are highlighted in the final section.

FUEL INJECTION SYSTEM DIAGNOSTICS FOR COMBUSTION ANALYSIS

During the intake process, fresh charge of air enters the cylinder of a diesel engine. At the start of compression, the cylinder contents are essentially air with a very small residual exhaust gas fraction. Towards the end of compression, when the piston is close to the top dead center (TDC) position, fuel is injected forming transient sprays. The mixture is very heterogeneous with liquid droplets, fuel vapor mixed with air, and some air pockets all present at the same time. The period of time from the start of injection to ignition is referred to as ignition delay (ID), and it is important not only from the timing point of view, but it will also, to a large extent, determine the nature of the combustion process in the diesel engine. During a long ignition delay period, a large amount of combustible mixture will be formed and a significant part of the fuel will burn rapidly in the premixed mode immediately after ignition. Once the premixed fuel is used-up, combustion becomes diffusion-controlled. If the delay is very small, depending on the conditions at the end of compression and the mixing process itself, burning is largely diffusion-controlled.

The injection, mixing and combustion processes are very complex and still difficult to model and simulate. Therefore experiments are an important aid in both graduate level teaching and combustion research. The ignition delay and the rate of heat release are the key phenomena that need to be analyzed in order to characterize and quantify the burning process. There are really two prerequisites for being able to perform that analysis: (i) the dynamic SOI needs to be determined with great accuracy, and (ii) cylinder pressure has to be measured during the same cycle. Subsequent heat release analysis of the in-cylinder pressure history based on the application of the first law of thermodynamics [2, 3] will produce the rate of heat release (RHR) profile; the latter initially has negative values, as a consequence of fuel evaporation, and dramatically rises after ignition. The instant at which the RHR line changes slope from negative to positive is considered to be the time of ignition [4, 5]. Therefore the ignition delay is commonly defined as:

$$ID = \Theta_{SOI} - \Theta_{IGN} \qquad (1)$$

where Θ_{SOI} and Θ_{IGN} are expressed in degrees crank angle (CA). Figure 1 illustrates this procedure and shows a typical RHR profile illustrating the premixed spike during the first phase of burning and the smaller gradients during the diffusion part of burning.

HIGH PRESSURE FUEL INJECTION SYSTEM BASED ON THE UNIT-INJECTOR DESIGN

The system of interest in this study is based on the unit injector design, hence all fuel injection functions are self-contained in a single unit. The injection pressure is developed by the piston plunger which forces fuel through the nozzle holes. The piston is pushed on by a rocker arm which is driven by a cam lobe on the camshaft. In order to prevent fuel from dripping through the injector nozzle after injection is completed, and compressed gas from flowing into the fuel system during compression, a spring-loaded needle check valve is included in the injector design. The fuel pressure must build-up to a value that produces a force exceeding the tension of the spring before the needle unseats and the fuel can start to flow through the injector holes. The injection line pressure is typically 5-10 times higher than engine peak cylinder pressure. The force acting on the plunger can be converted to units of pressure from the following expression:

$$p_{inj} = \frac{4F_{pl}}{{d_{pl}}^2 \Pi} \qquad (2)$$

where F_{pl} is the force acting on the plunger and d_{pl} is the plunger diameter.

With the aid of the electronic control module (ECM) on this engine, the injection timing can be specified and controlled for different operating conditions. An electromagnetic solenoid opens a poppet spill valve mounted on the injector body. When this poppet is held open, the fuel leaks so that injection pressure is not developed, therefore actual fuel injection is limited only to the time that the poppet is held closed and the injector plunger is being depressed by the cam. The start and end of injection can be independently controlled via a square wave signal from the engine's control computer.

INSTRUMENTING THE ROCKER ARM

Traditional SOI measurement techniques rely on hall effect position sensors to provide information about the injector needle movement [6]. SOI is then determined from the needle lift profile measured as a function of CA. In the unit-injector system under investigation here it would be very difficult to install such a device, because of the very complex design of the unit which incorporates both the pump element and the injector with very limited access to the lower part of the unit. However, the mechanism driving the unit-injector is exposed and easily accessible, thus making it an attractive option to instrument the rocker arm. By measuring forces on the plunger and by converting them to injection pressures, SOI can then be determined based on the known information about the injector opening pressure.

In developing this instrumentation system, two methods were tested, a half-bridge circuit and a full-bridge circuit [7]. The signal-to-noise ratio for the half bridge circuit given in Figure 2 was found to be superior, so this design was selected for all measurements presented in this paper. To make the half-bridge arm, a 90 degree strain gage rosette was cemented with heat-curing strain gage cement (M-bond 610) to the top flange of the rocker arm, as shown in the photograph of Figure 3. The rosette was placed midway between the rocker bearing and the tip that pushes the injector plunger, so that the force on the injector plunger can be measured most directly via the compressive strain in the upper flange of the rocker. Gage no. 1 reads strain along the top flange and is mounted on the centerline of the rocker, thus making the major contribution to the signal. Gage no. 2 is perpendicular to the axis and provides temperature compensation. As it is situated in an adjacent leg of the bridge, any strain that gage 2 picks-up due to thermal expansion of the rocker arm is canceled by an equal amount of strain appearing due to thermal expansion on gage 1. Some signal is picked- up on gage 2 due to tensile strain caused by expansion of the material in the direction normal to the centerline due to the Poisson's ratio effect. This effect contributes about a third as much resistance change in gage 2 as it does in gage 1 for the same load.

The gages used were Micro-Measurements WK-06-062-TT-350. This is a fully encapsulated, modified Karma alloy gage with glass fiber-reinforced epoxy-phenolic backing. This type has the most extreme environmental capability, and the short preattatched lead wires have high fatigue endurance. The 06 is the self-temperature compensating number which represents special processing to produce minimum thermal output in (ppm/^{o}C) over the range of -45 ^{o}C to 200 ^{o}C and it is selected to match the thermal expansion coefficient of the rocker arm material. The gages, solder pads and interconnecting wires were covered with a thin layer of M-bond GA-61 heat cured filled epoxy adhesive (not shown in photograph). This forms a very hard, chemical and oil resistant protective coating. The lead wires to the strain gages were strain relieved with an aluminum U-clamp gripping the cable jacket and screwed to the top of the rocker as near to the pivot as possible.

The strain gage amplifier used was a Micro-Measurements Group model 2310 system. This has built- in dummy resistors available to complete the bridge circuit when using a half bridge circuit. This amplifier has selectable filter cut-off frequencies. The wide band setting was used for this work so that maximum signal fidelity could be obtained. An excitation voltage of 10 V was selected since this gives the most signal output with an acceptable amount of self heating through the 350 ohm strain gage elements.

A calibration fixture was made with a spare cylinder head and pivot shaft. The rocker arm was placed upside down on the shaft and a cross bar was mounted in order to fix the position of the rocker roller. A cable was attached to the rocker tip to allow loading with a set of calibration weights. The calibration curve, i.e. amplifier voltage as a function of force is shown in Figure 4. An amplifier gain was selected to give a full scale amplifier output spanning a +/-5 volt range for a loading equivalent to the maximum expected injection pressure. Because the strain gages produce linear output, it is usually not necessary to cover the entire load range with calibration weights.

EXPERIMENTAL SET-UP FOR ENGINE TESTING

The heavy-duty diesel engine used in this study is set-up in the University of Michigan's W. E. Lay Automotive Laboratory with the aim of obtaining the signals from the injection system instrumentation and performing other high fidelity experimental measurements of the parameters needed for combustion analysis. An electric GE dynamometer (absorbing 600 HP / delivering 500 HP) is used to load and motor the engine. The engine is fully instrumented for pressure, temperature, rotational speed, mass flow and exhaust flow measurements. The instrumentation for the cycle-resolved measurements needed to study phenomena on a crank-angle basis includes an optical shaft encoder with quarter degree resolution, water-cooled piezo-electric pressure transducers installed in all six cylinders, and the strain gages mounted on the injection rocker arms for cylinders 3 and 6. The "high speed" data acquisition system is configured to simultaneously take up to 32 channels of cycle-resolved data at sampling rates of up to 200 kS/second. The system is based on the 16-bit VXIbus technology for the following reasons: quick system integration, reduced cable interconnect length, low system noise, and improved shielding. An embedded PC is used as the system controller. The LabVIEW[1] graphical programming software has been utilized to develop the data-acquisition and post-processing computer code.

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[1] LabVIEW is a trademark of the National Instruments Corp.

POST-PROCESSING AND ANALYSIS OF RESULTS

All results analyzed in this section are obtained from cylinder number 6 of the test engine which was instrumented with the half bridge strain gage configuration. Since cylinder number 3 was instrumented with the full bridge configuration which suffered from more noise, its results are not shown here. The engine was tested over the entire range of operating speeds (900 - 2100 rpm) and loads (10% - 100%). Data were also collected during motoring, i.e. when fuel was not being injected into the cylinders, and the dynamometer was used as an electric motor to turn the engine.

To extract from the raw firing signal the component of the force on the rocker arm solely due to fuel injection, the motoring rocker arm signal was subtracted from the firing signal (see Figure 5). The motoring, or zero load signal represents the force on the rocker arm due to the compression of the injector follower spring; the latter is being compressed with every rotation of the camshaft, whether or not fuel is being injected into the cylinder. The resulting signal is converted to units of pressure by using the strain gage calibration constant and the known plunger diameter (10 mm). The noise on the half-bridge configuration was negligible and the signal did not require any additional conditioning.

A sample set of injection pressure results obtained at the rated engine speed and different loads, i.e. different fuel system command settings, is given in Figure 6. The SOI at each of the operating points is determined from the intersection of the nominal needle opening pressure line with the injection pressure trace. Note that SOI is shifted significantly with changes in the input command. As load is increased from 20% to 80%, injection is advanced by more then 7 degrees CA, while at 100% load it is somewhat retarded again, probably to limit the peak combustion pressure and the mechanical stresses in the engine structure. Both the duration of injection and the peak pressure values vary significantly with load. This reveals an interesting feature of the injection system under investigation here: the fuel pressure increase is linear, even after the needle opens, hence the peak injection pressure increases significantly with load producing fine atomization of the fuel and enhanced mixing. Twenty consecutive cycles were recorded and statistically analyzed at each of the operating regimes. The standard deviation of the SOI angle in degrees varied between 0.029 and 0.125 for all regimes tested, thus indicating that cycle-to-cycle variations are small. The variations between individual cycles are the result of possible variabilities in both the real process and the measuring technique. The relatively small cycle-to-cycle variation in the SOI values suggests that both the injection system performs consistently and the measurement technique is reliable. Hence, it is possible to estimate SOI from injection pressure measurements with a relatively high degree of confidence. Testing of individual instrumented injectors on the injection rig prior to in-situ engine testing would further increase the confidence level by accurately determining the needle opening pressure.

CONCLUDING REMARKS

The electronic control of the injection process and the application of the unit-injector based system in the modern automotive diesel engine requires a novel approach to injection diagnostics. The dynamic start of injection (SOI) has been identified as one of the key parameters for combustion analysis. Appropriate instrumentation was applied to determine dynamic SOI based on the strain gage measurement of rocker arm force acting on the unit-injector plunger. The injection pressure is calculated from the force and the diameter of the plunger, while SOI is determined from the injection pressure profile and the known injector opening pressure. The technique presented here is suitable for use in both combustion research and laboratory instruction on internal combustion engines after some refinement of the data acquisition and post-processing software.

A series of measurements has been performed on a heavy-duty diesel engine, fully instrumented for cycle-resolved measurements of the rocker arm force and in-cylinder pressure with quarter-degree crank angle resolution. Analysis of results obtained for twenty consecutive cycles at each of the operating speed and load points indicates the following:

- The rocker arm signal obtained with the half-bridge strain gage configuration has excellent signal-to-noise ratio. The only conditioning required is the subtraction of the motoring signal, i.e. the force needed to compress the injector follower spring.

- The injection pressure increase is almost linear during the entire injection event, thus SOI can be determined with high accuracy. The phase shifts in SOI with changes of engine load can be very large, up to 7 degrees crank angle. However, during steady-state engine operation, the cycle-to-cycle variations in SOI are very small.

- The relatively small standard deviation in the SOI values determined for twenty consecutive cycles at each of the operating regimes indicates that both the injection and measurement systems are performing consistently. Therefore, it is possible to estimate the SOI from injection pressure measurements with a relatively high degree of confidence.

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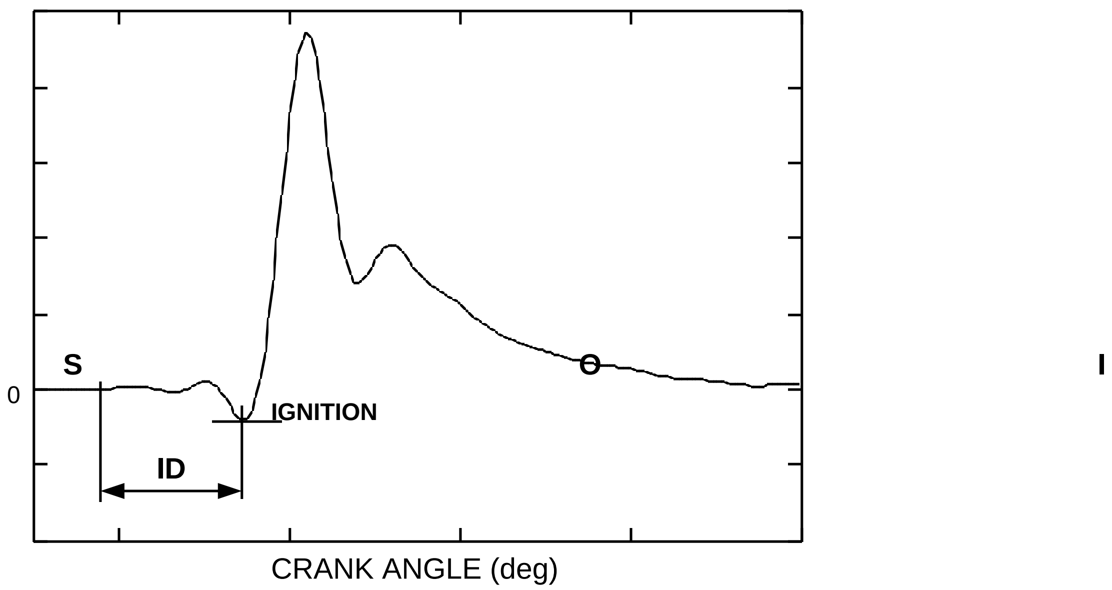

Figure 1 Determining the ignition delay from the Rate of Heat Release (RHR) profile.

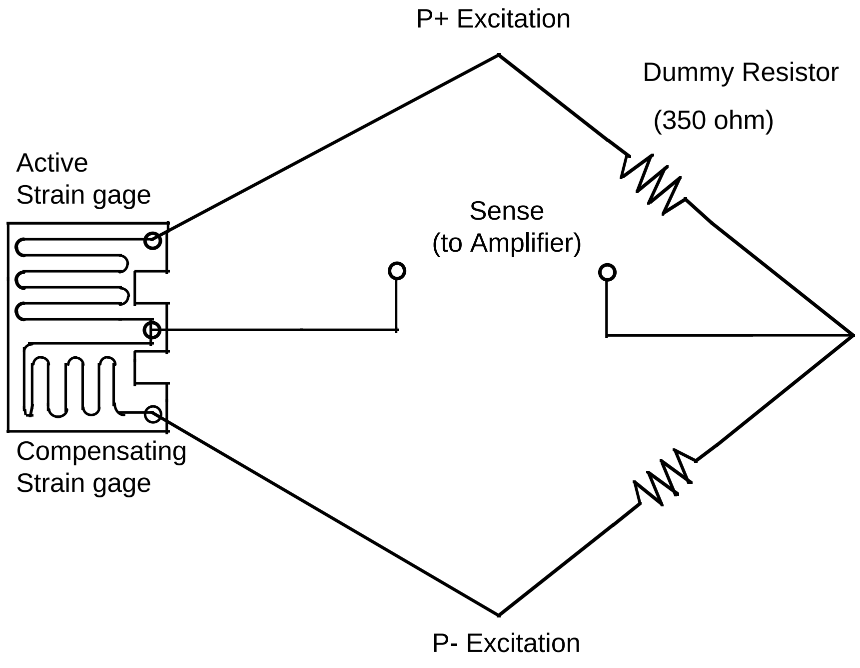

Figure 2 Wiring diagram of the half-bridge strain-gage circuit.

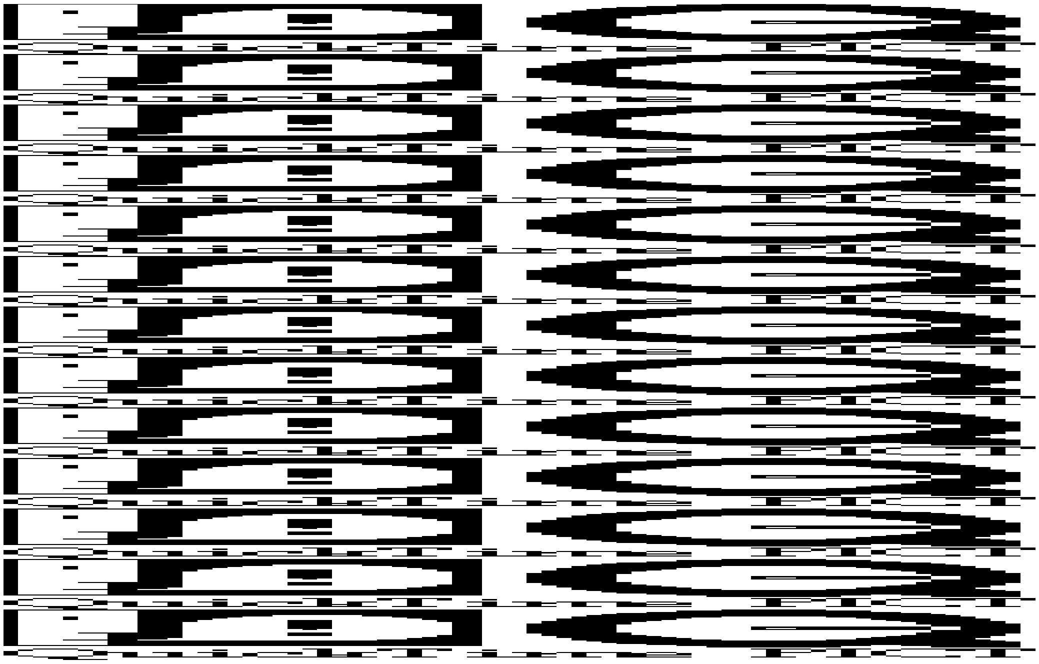

Figure 3 Photograph of the rocker arm with the installed strain-gage rosette.

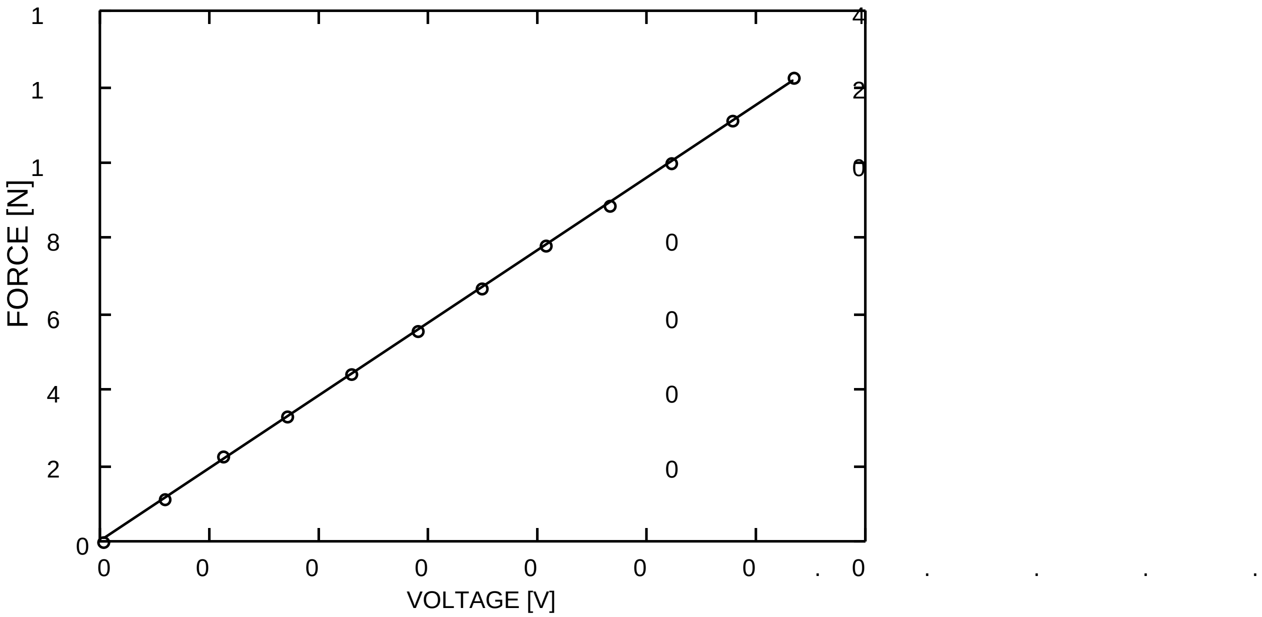

Figure 4 Strain-gage calibration curve.

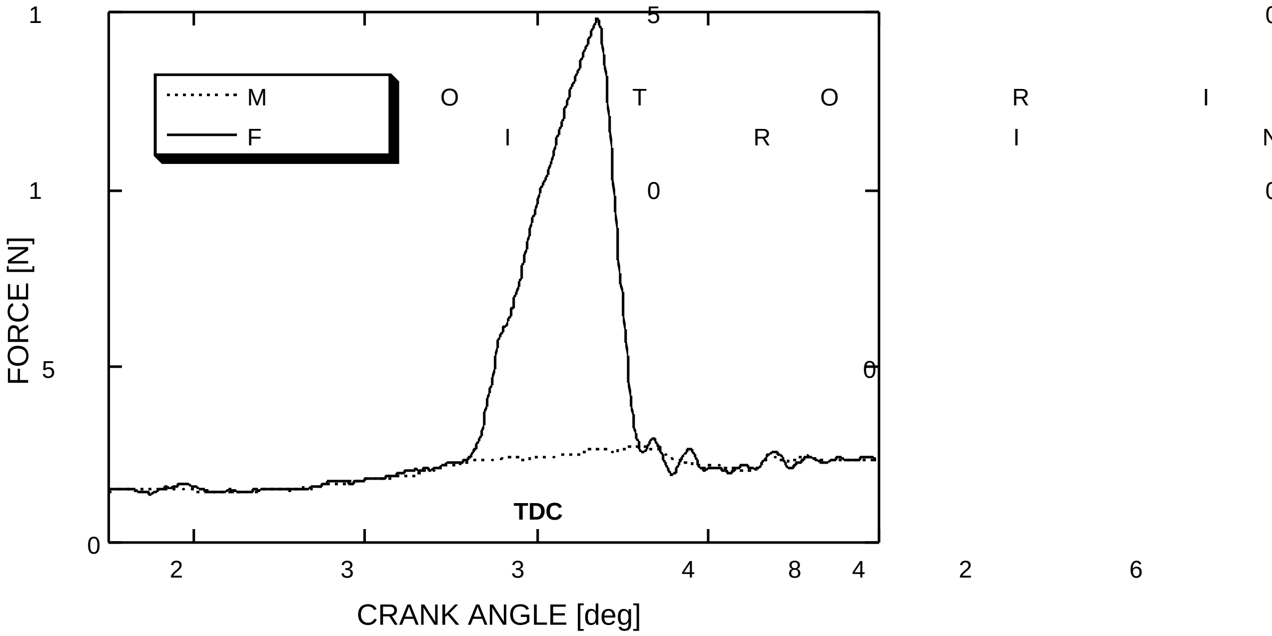

Figure 5 Force on the rocker arm during firing and motoring.

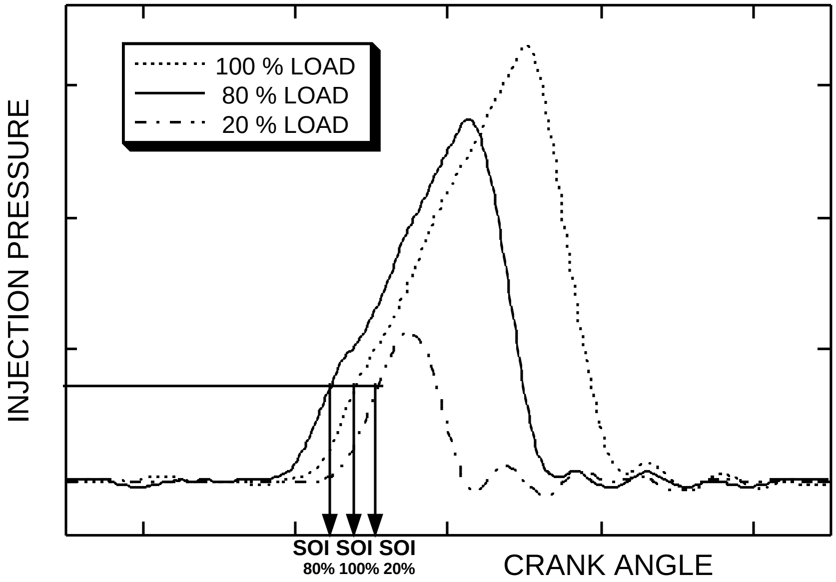

Figure 6 Injection pressure histories recorded at steady engine speed and 100%, 80% and 20% load points.