
J.D. Gill*, R.L. Reuben*, J.A. Steel*, M W Scaife† and J Asquith†

*Dept. of Mechanical and Chemical Engineering, Heriot-Watt University, Edinburgh. †Perkins Engines Co. Ltd., Peterburgh

SUMMARY

Acoustic emission measurements have been carried out on a Perkins T1004-4 high-speed, direct injection diesel engine. This is a turbo-charged four-cylinder engine of approximately 1 litre per cylinder. The AE sensor was attached to the injector body of cylinder four. By examining the raw AE signal acquired from this transducer during the injection and combustion period it has been possible to describe the effectiveness of fuel injection of diesel into the combustion chamber. These measurements have also demonstrated the possibility of application to other factors affecting the combustion process.

ABSTRACT

Cylinder pressure, needle lift pressure and high pressure injection line pressures (at both pump and injector) have been acquired over the complete operating range of a Perkins T1000-4 turbo-charged, four-cylinder high speed direct injection (HSDI) diesel engine. The engine is fitted with Perkins high-swirl ‘Fastram’ piston crowns and Bosch KD fuel injectors operated by a Bosch EPVE rotary fuel pump.

The work comprises a detailed study into the effect injector discharge pressure has on the acoustic emission (AE) response of the injector body. Two different fault conditions have been examined; injector discharge pressure reduced from 258 bar to 165 bar in all cylinders and injector discharge pressure reduced to 100 bar in cylinder 4 (instrumented cylinder). These two faults have been compared with the acoustic emission obtained under normal running conditions.

A comparison was also made with similar studies using vibration measurement, and it was found that the use of AE is more reliable at higher engine speeds and loads. This is due to the fact that the acceleration signal from the injectors suffers from severe interference caused by high amplitude, low frequency vibrations from structural resonances within the engine, specifically at high engine speed and load.

INTRODUCTION

Arguably the most influential component of the diesel engine is the fuel injection equipment (FIE); even minor faults can cause a major loss of efficiency and an increase in engine emissions and noise. The FIE requires the tightest of manufacturing tolerances and effective combustion is very dependent on the successful operation of each of the component parts. With increased sophistication (e.g. higher injection pressures, pulse injection and electronic control) being required to meet continuously improving noise, exhaust smoke and gaseous emissions regulations, the FIE is becoming even more susceptible to failure. This is mainly as a result of the ingress of particles into the system causing excessive wear and, for this reason, it is no surprise that injection systems have been shown to be the largest contributing factor to diesel engine failure [1]. Methods for successfully measuring the
effective operation of the FIE have invariably relied upon the use of intrusive transducers to measure a
erelated quantity, such as fuel injection pressure or cylinder pressure [2]. Some work has been
undertaken to examine the use of vibration monitoring of the injector body [3] with the aim of using its
response to diagnose the injector condition.

The largest problem with FIE is that small faults can easily manifest themselves without the end user
being able to attribute these directly to the injection system [4,5]. This can be because they are not
immediately noticeable or because the fault is so small that it does not necessarily show itself
immediately in terms of a significant loss of power or increase in emissions. This generally happens
with long-term wear and can allow damage to occur to other fundamental parts of the engine.

Both the vibration, and the significantly higher frequency acoustic emission responses of the injector
are likely to contain valuable information pertaining to the overall condition of the injection system.

EXPERIMENTAL SET-UP
The test engine was a Perkins T1004-4 turbo-charged, four cylinder high speed direct injection (HSDI)
engine developing 135 bhp at 2500 RPM. The engine was mounted on a skid and attached to a Froude
eddy-current dynamometer to control engine load and speed. The engine was fitted with a Bosch
EPVE rotary fuel pump and KD fuel injectors and was fully instrumented with injector pressure, in-
cylinder pressure and needle lift transducers on the cylinder being examined (cylinder four) as shown
in Figure 1. These were complemented by an array of acoustic emission (AE) transducers and
accelerometers. All of the above transducers were synchronized with the angular position of the engine
using a one-pulse-per-degree shaft encoder. After acquisition, the signal was re-sampled with respect
to the shaft encoder signal to remove any effects of fluctuations in engine speed during the cycle. The
AE sensors used were a combination of Physical Acoustics types D9203 and R301. The signals from
the transducers were bandpass filtered between 0.1 and 1 MHz and the rms AE signals were averaged
at 25 μs and sampled using a Microstar DAP 3000a/212 data acquisition board. The raw signals were
sampled at 5 MHz so that after re-sampling of the signal it was possible to obtain a minimum resolution
of 2.5 MHz to prevent aliasing of the signal.

![Figure 1: Perkins T1004 Cylinder Head Set-up](image)

Raw and rms acoustic emission measurements were obtained simultaneously with all other
measurements at engine speeds varying between idle and the full rated speed of 2500 RPM. Five
different load settings were examined, calculated as a percentage of full load at that speed. These were
0%, 25%, 50%, 75% & 100% load. Three different injector discharge pressures were examined to simulate damaged injector springs.

ACOUSTIC EMISSION MONITORING OF THE INJECTION PROCESS

Figure 2 shows a typical raw AE response from the injector body at 1500 RPM and 50% load for one full four stroke engine cycle re-sampled with respect to crankshaft position.

![Figure 2](image)
Raw AE Re-sampled wrt Crankshaft Position at 2.5 MHz. AE Sensor Attached to Injector Body of Cylinder 4

![Figure 3](image)
Cylinder 4 Injection and Combustion Period - Raw AE, Injector Needle Lift and Injection Line Pressure

The injector discharge pressure was set at 165 bar, as opposed to the factory specification of 258 bar, but is otherwise in good condition. The AE signal can be seen to display four distinct bursts related to the injection and combustion period of each individual cylinder. The most significant burst is that due to the injection and combustion in cylinder four, the injector on which the AE transducer was situated.

If the signal obtained from the instrumented injector is examined in more detail, Figure 3, it can be seen that there is an increase in AE activity at approximately 356° after top dead centre (TDC) of the firing stroke of cylinder one. This is believed to be caused by the build-up of diesel pressure in the high-pressure pipe-work. This is in contrast to the vibration signal that does not appear to show any signs of the initial build-up of pressure immediately preceding the lifting of the injector needle.

EXAMINATION OF FAULT CONDITION

Following examination of the normal operating condition, the injector discharge pressure in the instrumented cylinder (cylinder 4) was reduced to 100 bar to examine the effect this would have on the AE response. Figure 4 demonstrates the effect reducing injector discharge pressure has on the load speed curves for the engine. Much work has been carried out investigating, both mathematically and through visual examination, the effect injector pressure has on fuel-air mixing in the combustion chamber. It is agreed that, for an engine of this size, (1 litre/cylinder) impingement of the diesel spray with the wall occurs at between 8.5° to 11° after initial injection for an engine under full load. The majority of the air entrainment required for the mixture to reach the near stoichiometric condition occurs in the wall jet. Therefore, reducing the injector discharge pressure, as well as increasing droplet size, also increases the period before mixing of the fuel and air begins. The consequence of this is that
by the time the fuel is in a suitable state for ignition the peak cylinder pressure, and therefore temperature, has begun to fall.

Figure 4: Load / Speed Curves for Perkins T1004-4 Diesel Engine
Condition 1: Normal Running (Injector Discharge Pressure set at 258 bar)
Condition 2: Injector Discharge Pressure Reduced to 165 bar in all Cylinders
Condition 3: Injector Discharge Pressure Reduced to 100 bar in Cylinder 4

Figure 5 shows cylinder four injection and combustion period for normal running and for cylinder four injector discharge pressure reduced to 100 bar. The initial point of injection is earlier in the cycle for the reduced injector pressure and this is borne out in the AE response as the signal can be clearly seen to rise earlier than for the normal running condition.

Figure 5: Raw AE from Cylinder 4 Injector Body showing Cylinder 4 Injection & Combustion Period

However, the lower amplitude AE response from the injector body associated with the combustion process is extended for the fault condition. It is believed that this is a result of the less efficient mixing of the fuel and air. This necessitates a longer period for the adequate entrainment of air with the larger fuel droplets causing more erratic burning of the fuel.
As the speed increases, the period between fuel injection and combustion increases in terms of crank angle as the fuel takes a certain time to mix and for ignition to commence. To compensate for this, the fuel pump control automatically advances the start of delivery. Figures 6 a-d show the point of detection of the increase in pressure in the fuel line and the point at which the injector needle becomes fully open for four different speed conditions across the range of loads. These were calculated by rms-processing of ten raw AE cycles for each condition with an averaging time of 40μs and then calculating the mean and standard deviation for each point. As can be seen, the point of fuel line pressure increase and the maximum opening of the injector nozzle needle detected by the AE transducer is advanced with reduced injector discharge pressure.

![Figure 6a: AE Detection 1000 RPM](image)
![Figure 6b: AE Detection 1500 RPM](image)
![Figure 6c: AE Detection 2000 RPM](image)
![Figure 6d: AE Detection 2500 RPM](image)

Detection of Increase in Fuel Line Pressure (solid line)
Detection of Maximum Nozzle Needle Lift (dashed line)

**SUMMARY AND CONCLUSIONS**

The effect of reducing injector discharge pressure on the AE recorded on the injector body has been quantified using measurements on a test bed engine. As has already been demonstrated by other authors, notably Gu and Ball [3], the injector vibration and stress waves in the injector body are caused by a combination of mechanical and fluid-mechanical events. These events consist of impacts caused by the needle opening and closing and also by the high-pressure diesel flow through the pipe-work and nozzle. A number of these events are more easily detected using acoustic emission, notably the build-up of pressure in the high pressure pipe immediately prior to the injection process commencing.
Examination of the point of detection of the increase in fuel pressure and opening of the injector nozzle using AE have been shown to be good descriptors of the injector discharge pressure. Using this measure it is possible to detect the nozzle opening pressure of the injector without the need for expensive and intrusive sensors. The advantage of acoustic emission measurement over vibration measurement in this type of application is the significantly higher frequency of signal detected. This overcomes problems associated with engine resonances and low frequency vibrations caused by the operating environment (e.g. mobile applications, such as vehicles).

FURTHER WORK
Work is still being carried out into other fuel injector faults and the possibility of using a small array of acoustic emission sensors to detect a greater number of engine faults. Acoustic emission has so far been successfully applied to detect a variety of valve faults, gasket leakage and it has also been possible to reconstruct the cylinder pressure trace with an accuracy of ±5%.

The largest problem to be overcome in terms of using acoustic emission to detect faults on small diesel engines is the complexity of the AE signal at high speeds and loads. As can be seen in Figure 1 the signal acquired by a sensor mounted on one cylinder does not just relate to that cylinder. To overcome this problem will require some form of filtering or another technique which is currently being examined. This technique uses the transfer function, calculated using a piezo-pulser as a source, of the individual machine to eliminate unwanted components of the signal.

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the funding provided by the EC under its BRITE-EURAM programme, Project number BE96 3491.

REFERENCES


