Diesel injector dynamic modelling and estimation of injection parameters from impact response Part 2: prediction of injection parameters from monitored vibration

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Part 2 of this paper presents the experimental and analytical procedures used in the estimation of injection parameters from monitored vibration. The mechanical and flow-induced sources of vibration in a fuel injector are detailed and the features of the resulting vibration response of the injector body are discussed. Experimental engine test and data acquisition procedures are described, and the use of an out-of-the-engine test facility to confirm injection dependent vibration response is outlined.

Wigner–Ville distribution (WVD) analysis of non-stationary vibration signals monitored on the injector body is used to locate regions of vibration in the time–frequency plane which are responsive to injection parameters. From the data in these regions, estimates of injection timing and fuel pressure are obtained.

Accurate estimation of injection parameters from externally monitored vibration is shown to pave the way for the detection and diagnosis of injection system faults. Moreover, it is demonstrated that the technique provides an alternative method for the set-up, checking and adjustment of fuel injection timing.

Key words: fuel injector, condition monitoring, injector vibration, impact vibration, time–frequency analysis, injection pressure, injection timing

1 INTRODUCTION

The injection process plays one of the most influential roles in the performance and emission control of a diesel engine. Obtaining accurate values for injection parameters is the key to the specification, set-up, adjustment and diagnosis of injection equipment. This in turn permits enhanced performance such as reductions in fuel consumption and pollutant emissions, and increases in power output.

It is conventional to characterize the injection process in terms of injection pressure, needle lift and injection rate (the latter two factors contain injection timing information). Injection pressure is usually measured with a strain gauge transducer positioned in the high-pressure fuel line, and needle lift is measured with a displacement sensor inside the injector (**1**, **2**). Part 1 described why, due to their intrusive nature, it was inevitable that these measurement techniques would adversely affect the motion of the needle within the injector valve and would consequently change the fuel injection characteristics.

A non-intrusive measurement approach, which does not influence injection characteristics, is attractive because it may permit more accurate estimates of injection parameters. A further possible advantage of such an approach is that in-service condition monitoring with subsequent adjustment, fault detection and diagnosis becomes feasible.

Fundamental to the principle of non-intrusive measurement is the remote detection and interpretation of some transmitted quantity which contains sufficient information to enable the source parameter value to be inferred. Of the possible transmitted parameters, one of the most likely to contain the necessary information is the vibration response of the injector body to the operation of the injector valve within it.

Specifically, injector vibration response is due to a combination of the needle impacting and the flow of high-pressure fuel within the body. Using modern signal processing techniques and computational capabilities, it appears possible to extract injection parameter information from the non-stationary vibration signals that are detected by a transducer when positioned on the outer surface of an injector body.

In this study, the vibration response of a fuel injector when operating in a test engine is analysed using the Wigner–Ville distribution (WVD), and estimates of injection timing and fuel pressure are obtained. The layout of the paper is as follows: Section 2 analyses injector vibration; Section 3 describes the test methods used in the vibration measurement; Section 4 details the WVD analysis of the monitored vibration signals; and Section 5 compares vibration-based results with those obtained from conventional measurement.

2 INJECTOR VIBRATION

There are two sources of injector body vibration associated with the injection process: impacts due to the needle hitting its backstop and seat (that is mechanical excitation), and the flow of high-pressure fuel within the galleries and chambers of the injector (that is fluid flow

The MS was received on 4 April 1994 and was accepted for publication on 28 October 1995.

excitation). Aside from the nature of the excitation sources, the monitored vibration is also influenced by the dynamic properties of the injector body.

2.1 Mechanical excitation

In Part 1 the impact behaviour of an injector was investigated numerically by modelling the needle motion as a two-mass vibro-impact system. The retracting backstop impact was shown to be of lower amplitude but to contain more high-frequency components than the subsequent advancing needle seat impact. The first collision in the needle retracting impact series indicates the instant when the needle first reaches its fully open position. Similarly, the first collision in the needle advancing impact series indicates the instant when the needle first returns to its seat.

Part 1 developed a theoretical correlation between the impacts and fuel injection parameters. The amplitude of the first collision in the opening impact series was shown to be related to the fuel injection pressure, and the energy of the opening impact series was shown to be related to the fuel injection rate.

2.2 Fluid flow excitation

During injection, fuel flows through the internal passages and chambers of the injector with a sharp high-pressure wave front. This turbulent flow impinges upon the injector body and causes it to vibrate. The forces involved are proportional to the dynamic head of the fuel flow and the frequency of the resulting vibration depends upon the sharpness of the wavefront. This means that injection at larger fuel rates is more likely to produce higher frequency and larger amplitude body vibrations than injection at smaller rates.

The presence of flow induced vibration response is confirmed in Fig. 1 which overlays monitored body vibration upon cylinder pressure, line pressure and needle lift traces. From this figure it can be seen that there is a vibration response commencing prior to the opening of the needle (at a time corresponding to the onset of high-pressure fuel supply) and continuing until the needle is fully retracted, at which point it becomes swamped by the high-amplitude impact response. In this time span, there are no mechanical impacts, only the flow of fuel within the injector.

2.3 Injector body response

Due to the short duration of the collisions which comprise the opening and closing impact series (the duration of a collision is of the order of a microsecond), the injector vibration response to this excitation is a sequence of three series of transients, with each transient being dominated by the lower body frequencies. Within an injection cycle, the order of the excitation events dictates that the first transient series is due to flow excitation, the second transient series is due to opening impact excitation, and the third transient series is due to closing impact excitation.

Depending upon engine operating conditions (for example the duration of injection), an individual transient response within the train of responses may or may not have decayed completely before the next transient occurs. As shown in Part 1, the opening and closing impact series have different spectral contents, meaning that their associated responses will have different spectral contents too. From a time trace of monitored vibration, it may not be possible to detect the instant of the closing impact if it is buried in the continuing transient response from the opening impact series. The different frequency contents of the two responses suggest,

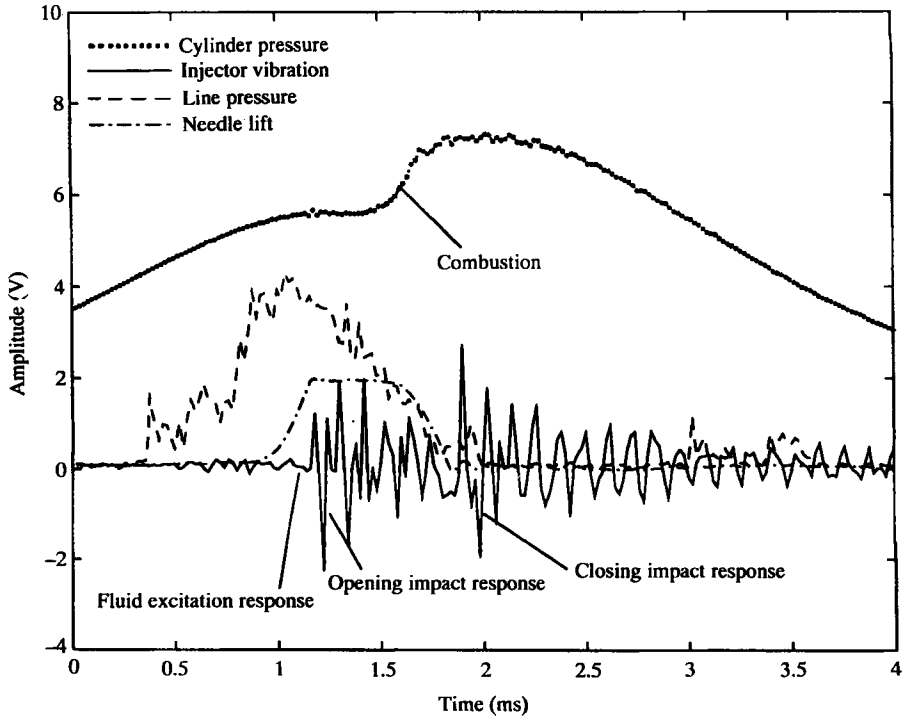


Fig. 1 Injector vibration versus cylinder pressure, line pressure and needle lift

however, that it should be possible to differentiate between the two events if the monitored vibration response is transformed into a time–frequency representation.

3 INJECTOR VIBRATION MEASUREMENT

Due to the complex nature of the injector body, its mounting assembly and its interaction with the cylinder head, it is difficult to derive a mathematical model relating the internal vibration sources to an external surface-mounted monitoring transducer. For this reason, an experimental investigation of the relationship between monitored vibration and fuel injection was adopted in this study.

Two types of experimental set-up were used: a working engine test rig, and a bench-top rig providing an out-of-the-engine injection test facility. The test engine was a Ford FSD-425 production unit fitted with a Bosch V injection system and coupled to a hydraulic dynamometer. The bench-top test rig comprised a cylinder head from another Ford FSD-425 engine and fitted with an identical injection system, but driven by an electric motor. The purpose of the bench-top rig was to isolate those components of monitored vibration which were due to the injection process from those components associated with combustion, piston slap and other engine sources. In addition to the recording of injector vibration when in the test engine, fuel line pressure, needle lift and fuel consumption were recorded by conventional methods to enable the relationship between the injection parameters and vibration to be investigated.

3.1 Bench-top injector tests

In addition to the internal sources of diesel injector vibration, it is likely that other factors, particularly combustion noise, will also excite the injector body. During combustion, there is a sharp rise in cylinder pressure and a consequent shock which acts upon the cylinder head, cylinder wall and the tip of the injector nozzle. This shock to the injector tip, and the vibration of the cylinder head, are likely to contribute to the vibration response of the injector body.

Figure 1 (in Section 2) shows that there is no severe cylinder pressure change at the time of injector needle opening, and it is hence unlikely that the cylinder pressure makes any significant contribution to injector body vibration. At the time of the injector needle closing, however, the cylinder pressure rises sharply with the onset of combustion, and it is hence unlikely that the injector body vibration is due to needle impacts alone. Ascertaining the sources of excitation during the needle closing phase is not straightforward, and this difficulty provided the motivation for the development of the bench-top injector test rig.

Figure 2 depicts the schematic layout of the bench-top rig, which was designed to isolate injector vibration response from all sources aside from those inherent to the operation of the injector. The principal components of the rig are a variable speed electric motor driving an injection pump, which in turn supplies fuel from a tank to a set of four fuel injectors, one of which is mounted in a cylinder head. To ensure close correlation with the engine tests, the injection pump, injectors and cylinder head are identical to those used on the engine. Supports shrouded in damping material, and vibration isolating mounts are employed to minimize the transmission of vibration from the motor and the fuel pump to the test injector.

Only one injector (the test injector) is mounted in the bench-top cylinder head. The other three injectors, used to maintain representative loading of the injection pump, are mounted together in a dummy cylinder head with associated fuel collection vessels. This separation of the test injector from the load injectors is further to ensure its vibration isolation. Fuel levels can be adjusted via the injection pump rack setting in the usual way, and the pump speed can be varied by the closed-loop

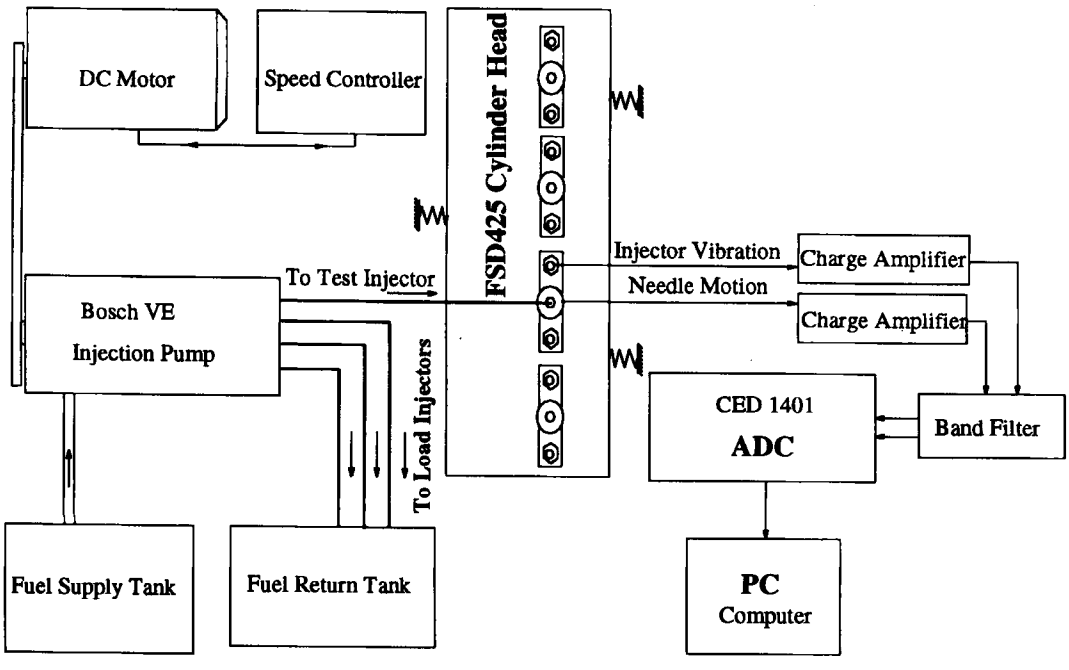


Fig. 2 Bench-top test rig layout and data acquisition system

motor controller. Two-channel data acquisition from the bench-top rig was made with a computer-controlled 12-bit device sampling simultaneously at 65 kHz. The incoming data streams of body vibration and directly measured needle motion readings were gated in software into 1024-point segments.

From the bench-top tests, several aspects of injector vibration response were confirmed. By comparing the vibration signal in Fig. 3(a1) with that in Fig. 1 (which was obtained from an engine test) it can be seen that the two body response waveforms are very similar. From this similarity it can be concluded that combustion shocks, piston slap and other engine operating sources have minimal effect upon injector vibration response. Such response is only a consequence of mechanical and flow-related vibration sources within the injector. This conclusion is reinforced by the directly measured needle acceleration traces shown in Figs 3(a2) and 3(b2). Of particular interest in Fig. 3 is that the upper (a1 and a2) traces are from a high-load situation, where both opening and closing needle impacts are apparent, whereas the lower traces (b1 and b2) are from a low-load test in which it can be seen that there occurs no opening impact of the needle with its backstop.

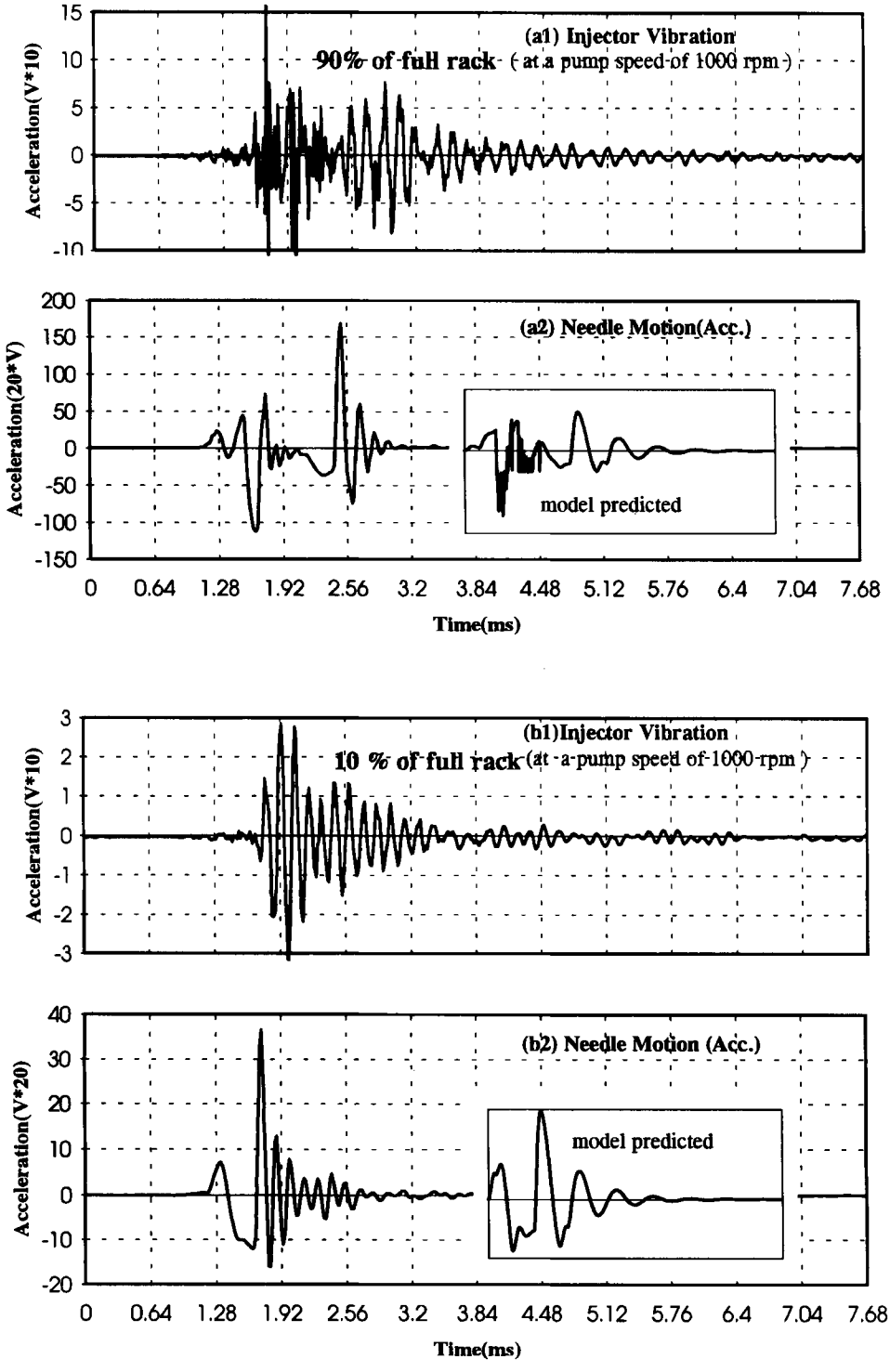


Fig. 3 Injector vibration and needle motion from bench-top testing

The inserts within Figs 3(a2) and (b2) show the acceleration waveforms as predicted by the model developed in Part 1. These can be seen to exhibit quite a good correlation with their measured equivalents, further validating the accuracy of the model.

3.2 Engine injector tests

The specification of the test engine is given in Table 1. This engine is mounted on a test bed and is coupled to a hydraulic dynamometer, with speed and load settings controlled from a remote console. More details of the engine test bed can be found in reference (2).

Figure 4 depicts a schematic of the engine test bed and its associated instrumentation. A computer-controlled multi-channel data acquisition system was used to capture signals with a synchronous sampling rate of 50 kHz and 12-bit resolution. Four channels of data were recorded: cylinder pressure, fuel line pressure, directly measured needle lift and injector body vibration. The body vibration response was bandpass filtered between 2 Hz and 24 kHz. The cylinder pressure was measured directly using a flame front transducer and the pressure of the fuel line was measured by a strain gauge transducer located approximately 150 mm from the injector nozzle. The test injector was modified to incorporate an inductance sensor for needle lift measurement, the engine speed was determined from a crankshaft encoder, the engine torque was obtained from an output shaft load cell, and the fuel consumption was measured with a flow meter.

Table 1 Test engine specification

Engine type	Ford FSD-425 DI
Number of cylinders	Four
Bore	93.7 mm
Stroke	90.5 mm
Swept volume	2.495 litres
Combustion system	Direct injection diesel
Compression ratio	18.3 : 1
Fuel injection pump	Bosch type V
Fuel injector nozzles	4 × 0.24 mm
Rated speed	66.7 r/s
Aspiration	Natural

Before conducting a test, the engine was run to normal operating temperature, and then a constant speed test was performed at four load settings between 35 and 130 Nm. In all, three test speeds of 2000, 2500 and 3000 r/min were used. With this test procedure, a wide range of operating conditions, and consequently of fuel injection characteristics, was covered. In the same manner as for the bench-top rig, the incoming data was gated in software to give 1024-point segments.

4 TIME–FREQUENCY ANALYSIS

As shown in Figs 1 and 3, the vibration responses of the injector body are highly non-stationary, and Part 1 discussed why the needle opening and closing impacts contain differing frequency contents. The body responses to the flow and impact excitation are transient in form, with amplitudes that start large and decay with time. Time–frequency methods provide a convenient and powerful way to analyse this type of signal. Of the many time–frequency methods, the WVD has received considerable attention because of its relative simplicity, optimal energy concentration and straightforward computational implementation.

The version of the WVD that was used for the analysis of the injector body response is detailed in the Appendix to this paper. In addition to its basic properties, the WVD was shown in reference (3) to be powerful in the extraction of short duration transients from noise contaminated signals. Figure 5 shows a typical WVD three-dimensional mesh plot of monitored injector vibration. This type of mesh plot shows the distribution of vibration energy over the time–frequency plane. Sudden changes in amplitude indicate the injector

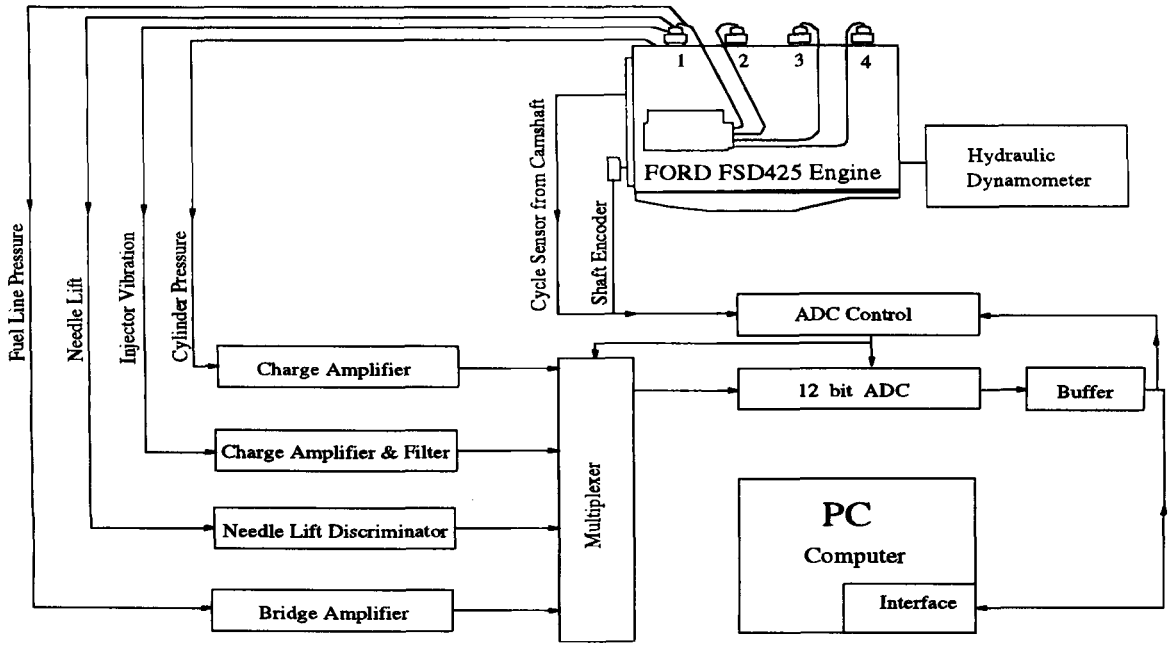


Fig. 4 Engine test layout and data acquisition system

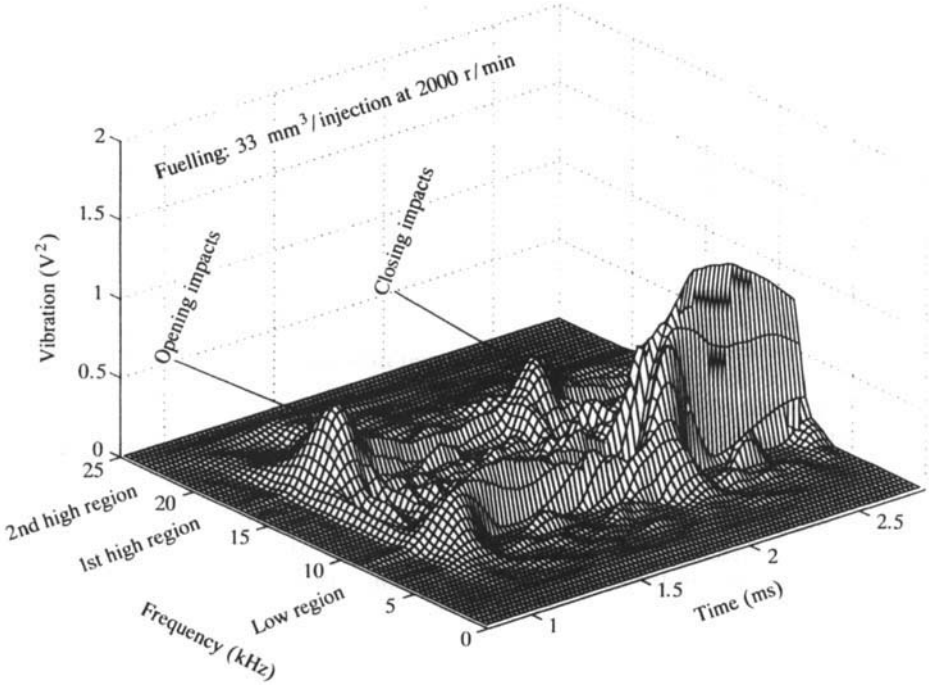
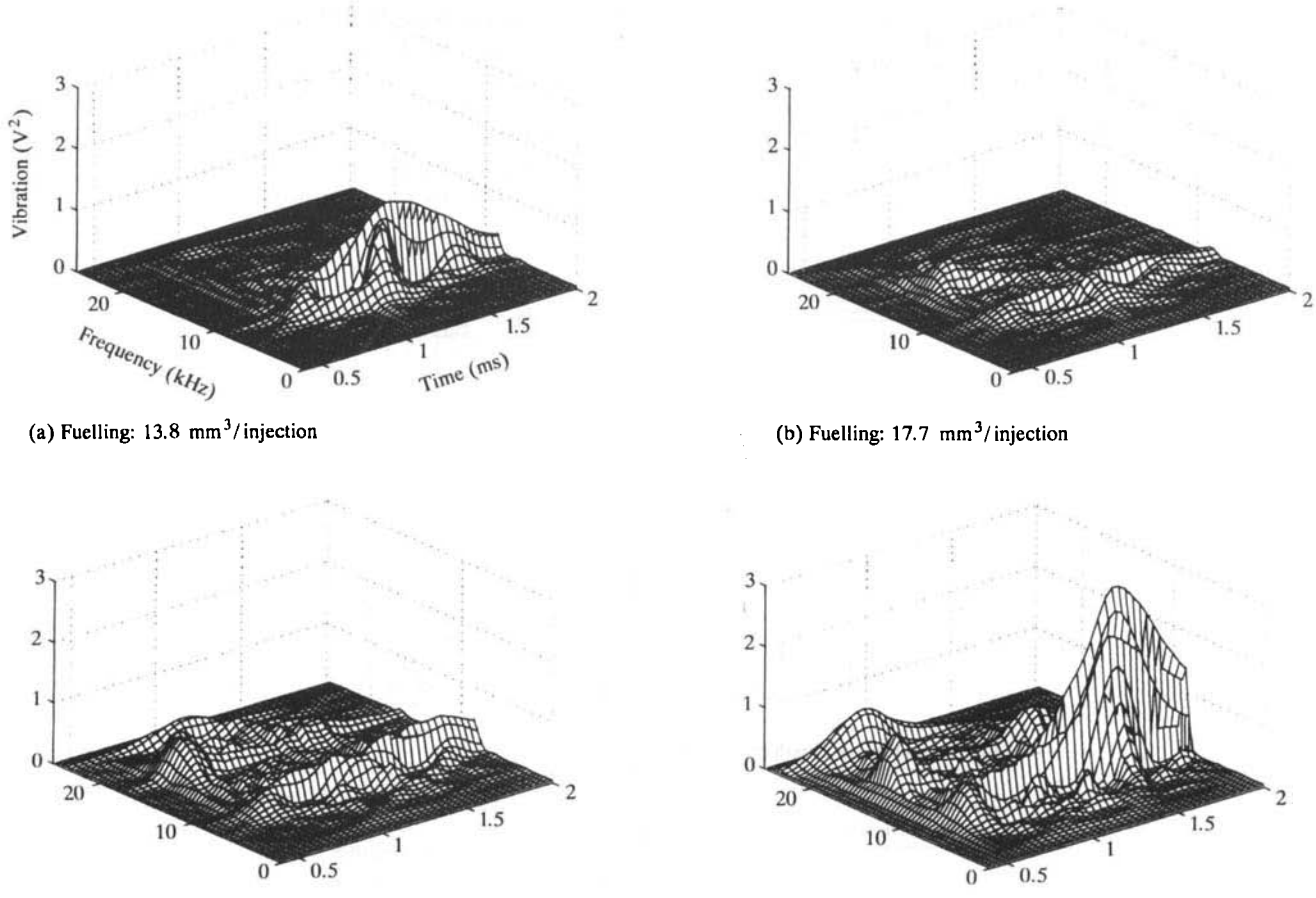


Fig. 5 Time–frequency analysis of injector vibration

responses to the impacts at the start and end of injection.

It can be seen that during injection, vibration energy is spread over a wide range of frequencies from around 5–24 kHz, and that there are three main frequency response ridges with values of around 9, 17 and 23 kHz. The opening impact responses are seen to attenuate gradually with time and the two higher frequency



(a) Fuelling: 13.8 mm³/injection

(b) Fuelling: 17.7 mm³/injection

(c) Fuelling: 13.3 mm³/injection

(d) Fuelling: 31.2 mm³/injection

Fig. 6 Time–frequency analysis of injector vibration at 3000 r/min

response ridges have all but disappeared by the time that the injector closing impact occurs. The frequency response to the impact of the needle closing can be seen to be of a narrower frequency content and is dominated by activity in the 9 kHz region.

Figure 6 shows WVD analysis results for differing engine loads at a speed of 3000 r/min. From this figure it can be seen that there is a clear increase in the amplitudes of the higher frequency vibration response ridges with increasing fuelling (that is load). This behaviour is important because it agrees with the predications made by the impact force simulation that is described in Part 1.

Although it is clear that there is considerable variation with load of the low-frequency (9 kHz) region, this variation is less predictable than the corresponding high-frequency activity. Furthermore, it is more difficult to distinguish the injector closing response in the low-frequency region. For these reasons, the low-frequency ridges were deemed unsuitable for the analysis of the fuel injection process.

The vibration levels associated with the needle closing impact response can be seen to vary somewhat erratically with fuelling. There are several possible reasons why this may occur, of which a likely consideration is the unrepeatability of the fluid dynamics governing the closing needle motion. The needle opening is governed by a large and repeatable fuel pressure front, but the needle closing is governed by the residual pressure in the injector, and this is likely to vary quite considerably from injection to injection. If the residual fuel pressure is low, it is likely that a large amplitude body response will result. Conversely, if the residual pressure is high, the needle return motion will be more damped and will give a smaller vibration response. High levels of body response to needle closing are therefore likely to be indicative of clean and rapid closing, whereas low levels of response are likely to be indicative of less than ideal closing behaviour, possibly causing secondary injection and consequent nozzle fouling. There appears to be scope for the use of closing response patterns in the detection of inappropriate injector behaviour.

5 ANALYSIS OF THE INJECTION PROCESS

Having identified within the WVD analysis those regions of frequency response which contain injection related information, bounds can be placed upon the frequency range of interest. With these bounds it is possible to set a bandpass filter so that envelope analysis can be used as an alternative means of extracting the appropriate high-frequency information from the monitored vibration data. The use of envelope analysis as an alternative to WVD analysis is, in certain circumstances, attractive because it is more straightforward to implement, quicker to use, and gives a representation of amplitude rather than energy content of a signal.

5.1 Extraction of timing information from monitored vibration

Injection timing is characterized by three events which can be observed from a needle lift diagram:

(a) the instant of the needle starting to retract identifies the start of injection;
(b) the fully retracted needle condition identifies the valve as being fully open; and
(c) the instant of the needle returning to its seat identifies the end of injection.

The upper part of Fig. 7 depicts the occurrence of these three events on a needle lift diagram.

The lower trace in Fig. 7 shows the 16–23 kHz envelope of monitored vibration, aligned in time with the needle lift diagram above it. From these traces it can be seen how the injection timing events correlate with the wavefronts of a normalized time signature. It can be seen that the needle opening event occurs at a point in

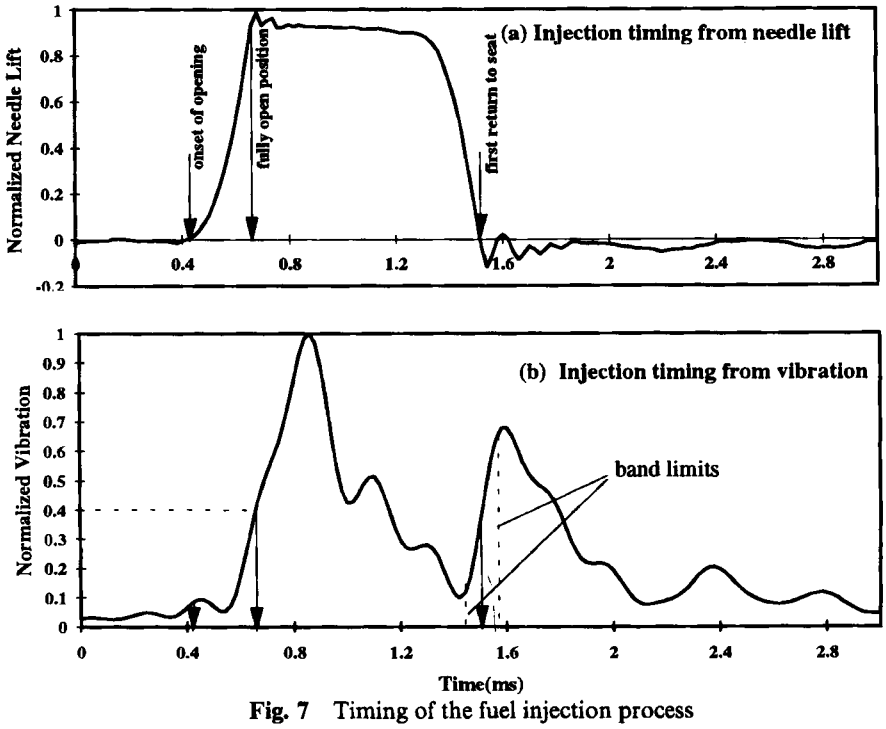


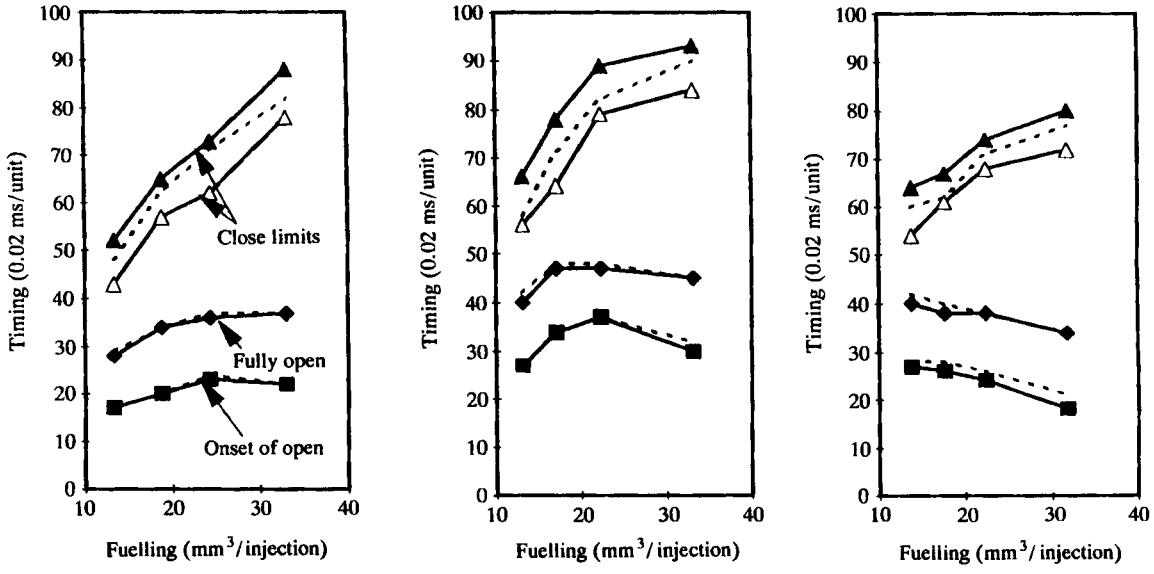
Fig. 7 Timing of the fuel injection process

time corresponding to around 50 per cent of the peak of the first time response wavefront, and the needle fully open event occurs at a point when the second time response wavefront has attained approximately 40 per cent of its peak value. For reasons discussed earlier, the time response to the needle closing impact is not as stable as the responses to the other timing events, and for this reason, a time band rather than a discrete time point was used as indication of the occurrence of the needle closing event. The occurrence of the valley immediately preceding the closing response wavefront was taken as the starting point of this time band, and the finishing limit of the band was taken as a point in time corresponding to the wavefront attaining 80 per cent of its peak value.

A comparison between needle lift and envelope-derived timing information is presented in Fig. 8. It can be seen that the values of the injection events obtained from the monitored vibration time signature are highly consistent with those obtained by direct needle lift measurement. The vibration-derived timing of the needle opening and fully open events is nearly identical to the equivalent needle lift information, and the vibration-derived band of the closing event timing neatly contains the directly measured trace. It can be seen from the closing impact bands depicted in Fig. 8 that averaging of the band limits does, in the majority of instances, give a timing value for the needle closing event which is very close to that obtained by needle lift measurement.

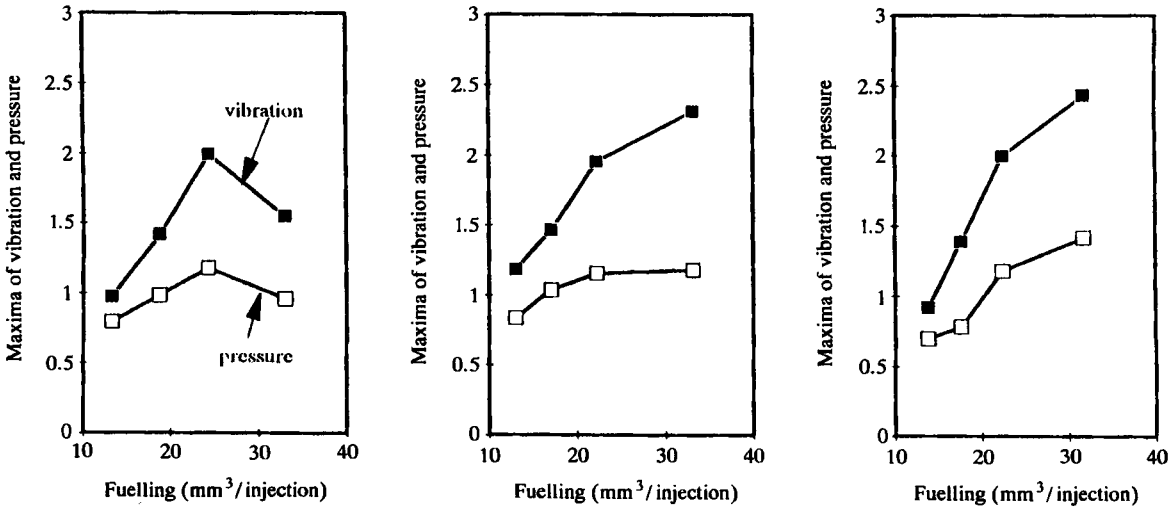
5.2 Extraction of fuel pressure information from monitored vibration

Part 1 showed that there is a clear model-predicted correlation between opening impact force and associated fuel injection pressure. Based upon this finding, it seems likely that there exists a similar correlation between the amplitude of injector vibration response to the opening impact series and the pressure of the fuel being injected. Figure 9 depicts measured peak fuel line



(a) Speed = 2000 r/min (b) Speed = 2500 r/min (c) Speed = 3000 r/min

Fig. 8 Comparison of needle lift and vibration derived injection timing



(a) Speed = 2000 r/min (b) Speed = 2500 r/min (c) Speed = 3000 r/min

Fig. 9 Comparison between injection line pressure and injector vibration

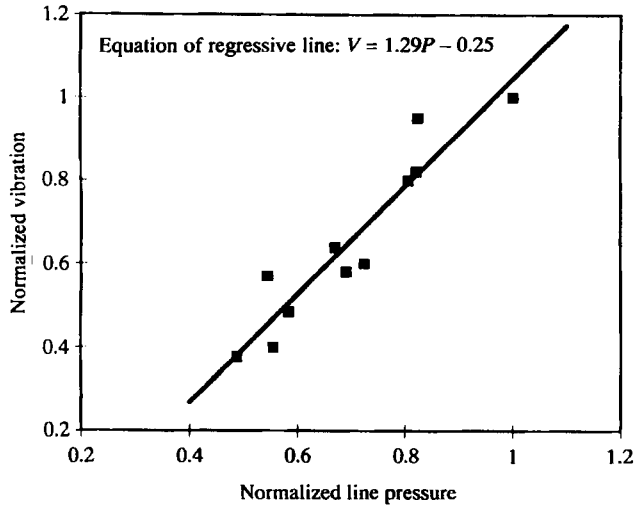


Fig. 10 Relationship between injector vibration and line pressure

pressure and monitored peak vibration values against fuelling. The shapes of the vibration and line pressure plots can be seen to be quite similar. Regression of the vibration and pressure data, as shown in Fig. 10, reveals a linear relationship.

The straightforward linear relationship between vibration and pressure has obvious uses in injection process analysis and condition monitoring. The ability to predict injection pressure from a suitable measurement of vibration amplitude would enable the analysis of injection spray quality without modification of the injection system and its consequent adverse effects. From the viewpoint of diesel engine condition monitoring, common injector faults such as leakages, reduced spring rates and needle wear will change the slope of the regression line, and the correlation coefficient will deviate the value associated with the injector when in good condition. There is clear scope for further work in the development of injection system fault detection and diagnosis techniques based upon monitored vibration.

6 SUMMARY AND CONCLUSIONS TO PART 2

A vibration based non-intrusive approach to the estimation of key diesel fuel injection parameters has been developed and has been applied successfully to a conventional pump pipe nozzle system on a test engine. From this work, the following conclusions can be drawn:

1. Injector vibration is caused by a combination of mechanical impacts and high-pressure fluid flow within the injector body. This vibration response can be detected using an accelerometer mounted either on the injector body, or on the injector fixing saddle.
2. An engine-isolated bench-top rig was used to demonstrate that injector vibration response is not contaminated by engine-related vibration sources such as combustion noise and piston slap.
3. Wigner–Ville distribution analysis was applied to the highly non-stationary vibration signals monitored on an injector body and this showed that the high-frequency body response contains regions of information which describe the injection process.
4. It has been shown that injection event timing details can be extracted from monitored vibration, and that these details bear close correlation with those obtained from the direct measurement of needle displacement.
5. The correlation between the needle opening impact series and injection pressure, as postulated by the model of Part 1, has been confirmed. It has also been revealed that there exists a linear relationship between the injector vibration amplitudes and fuel supply line pressure.

The proposed vibration-based non-intrusive approach to the analysis of diesel fuel injection systems could provide a powerful alternative to the conventional intrusive fuel line pressure and the needle lift measurement techniques that are commonly used. In addition, this technique has important implications in the field of diesel engine condition monitoring. Deviations from the demonstrated good condition relationships between monitored vibration and fuel injection parameters will be likely to indicate a change in condition. There is clearly a considerable amount of further work to be performed if the information contained in monitored injector vibration is to be used to the full, and further research work is currently being performed.

ACKNOWLEDGEMENTS

Thanks are due to Professor D. E. Winterbone of the Mechanical Engineering Department at University of Manchester Institute of Science and Technology for the use of the engine test facility.

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APPENDIX

The Wigner–Ville distribution (WVD)

The discrete WVD of a digitized signal $f(n)$, can be expressed as follows (**4**, **5**):

$$W_{f_m}(n, m) = 2 \sum_{k=-N+1}^{N-1} |w(k)|^2 \times f(n+k) f^*(n-k) e^{-2jk\pi(m/L)} \quad (1)$$

In this expression, a truncating window $w(n)$ has been used. The bi-linear nature of the WVD transform gives rise to interference terms in both time and frequency. The truncating window assists in suppressing the time-interferences, and it is common to use a smoothing window $g(n)$ to suppress the frequency-interferences, as

follows:

$$SW_{ff}(n, m) = \sum_{p=-Q+1}^{Q-1} W_{f_m}(n, m)g(n-p) \quad (2)$$

Equation (1) reveals that the WVD can be evaluated using a conventional FFT algorithm, and this procedure is quite efficient. Use of the analytical version of the original real value signal in the FFT ensures that aliasing does not occur. Moreover, because the conjugate multiplication of the analytical signal gives symmetrical results, it need only be performed over half of the truncating window length. A single execution of the FFT algorithm gives rise to two successive WVD lines.

A significant advantage of the WVD is that the truncating and smoothing windows can be applied independently so that the desired frequency and time resolutions can be obtained together. Other properties of the WVD, like its optimal energy concentration and its finite time–frequency support, make it further suitable for injector vibration analysis.

During the processing of injector vibration a Kaiser window was used as the truncating window function. Its length was set to 64 samples, giving an acceptable trade-off between frequency resolution and time-interference suppression. A rectangular window function of length eight samples was used for the smoothing window to maintain good time resolution. The WVD results are presented as three-dimensional surface meshes to give a better understanding of the distribution of injector vibration energy on the time–frequency plane. All analytical procedures were coded in Matlab and executed on either a 486 PC or an HP-700 machine.

