Measuring the needle lift and return timing of a CRDI injector using an accelerometer

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Abstract—The needle lift and return timing of a CRDI (common rail direct injection) injector were investigated using an accelerometer and the Bosch injection rate measurement method. The Bosch method was used to measure the fuel injection rate shape when fuel was injected with several patterns. An accelerometer was mounted on the outside of the injector to catch the needle lift and return timing of the injector according to the switching signal of the injector driving voltage. The accelerometer accurately caught the timing of the injector needle lift and return for a single-injection pattern, but it could not for the second or third injection when multiple injections occurred. Only the first needle lift timing of the injector was caught with the injection rate shape obtained from the Bosch method, however, this method cannot identify any other lift or return timing values after the first lift timing.

Keyword-needle lift, needle return, diesel engine, accelerometer, injection rate shape, common rail

I. INTRODUCTION

The fuel injection timing in diesel engines has a decisive effect on the engine performance torque, power, fuel consumption and emissions [1]-[3]. Additionally, it has a trade-off relationship with the smoke and NO_x emitted by the engine. Recent advancements in diesel engine technology, with the introduction of common rail and solenoid injectors, have allowed the electronic control of fuel injection [4], [5]. A mechanical type of fuel injection system is capable of controlling the injection timing in a specific pattern using a mechanical timer, though multiple fuel injections with such a system are nearly impossible. The transformation to an electronic control system for diesel fuel injection has completely removed the previous limitation in varying the fuel injection timing according to the engine operation condition. Also, different fuel injection patterns, such as pilot, split, and multiple injections for optimal engine performance, have been realized by adopting the electronically controlled common rail fuel injection system [6]-[8].

To measure the fuel injection timing most accurately, the lift of the needle in the injector must be measured. The moment that the needle is lifted indicates the beginning of the fuel injection, and when the lift hits zero, the fuel injection ends. Another method to determine when fuel injection starts is to measure the fuel injection rate shapes and analyze them. In analyzing the shapes of the fuel injection rates, the injection timing and amount injected can be identified. Common methods used to measure injection rates in diesel injectors are the Bosch method [9] and the Zeuch method [10], but recently a new method that measures the voltage produced when the fuel hits a metallic sensor has been reported as well [11]. A method that measures the amount of fuel injected from each hole for a multi-hole injector has also been developed [12].

Measurement of the fuel injection rate and timing are vital, as these parameters are key elements that determine the performance of diesel engines. In this study, for research purposes, the author assembled an injection rate measurement device for a common rail injector that uses the Bosch method. To evaluate the viability of applying an accelerometer to catch the lift and return timing of the needle in a CRDI injector, the accelerometer was attached onto the outside of the injector to measure the time from the moment the needle was lifted to the time it returned. The accelerometer method is extremely simple, as it only involves attaching it to the outside of the injector. There is almost no existing research on injection timing measurements using an accelerometer. The measured timings were compared to the actual signals that started and ended the fuel injection process.

II. EXPERIMENT

Fig. 1 shows a schematic diagram of a typical fuel injection control scheme according to the lift and return position of the needle in the injector. The fuel injection starts and fuel is injected through the nozzle holes, as shown in Fig. 1(a). The needle is lifted when the solenoid in the injector is activated. Fuel injection terminates when the needle returns to its initial position as soon as the solenoid is deactivated, as shown in Fig. 1(b). Fig. 2 presents a schematic diagram of the entire experimental setup. The experimental apparatus includes a high-pressure fuel pump powered by an AC motor, a common rail, an injector, a throttle valve, a pressure control valve, a brass tube, and a scale. The measurement system consists of a pressure sensor, an accelerometer, a charge amplifier, and a digital oscilloscope.

The AC motor, which is directly connected to the high-pressure fuel pump, is rotated at a constant velocity, which pressurizes the common rail at a constant pressure. The fuel pressure leading to the injector is then monitored by the common rail pressure sensor while being manipulated to reach the target pressure. The common rail pressure is controlled by adjusting the voltage of the fuel pressure controller through a potentiometer. As the common rail pressure reaches the target pressure and is then maintained at the target pressure, the power voltage supplied to the injector is switched on in order to drive the injector. The fuel injection period depends on the length of time that the switch is on.

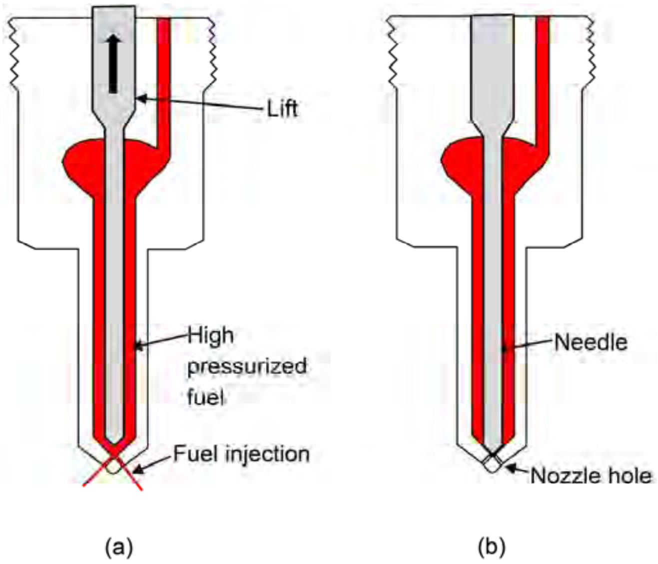


Fig. 1. A schematic diagram of a typical fuel injection control scheme according to the (a) lifted and (b) returned position of the needle in the injector

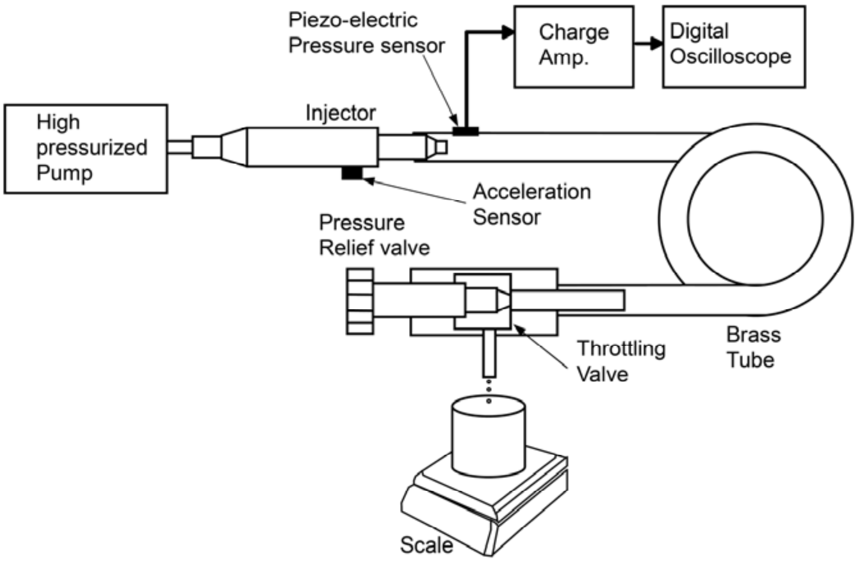
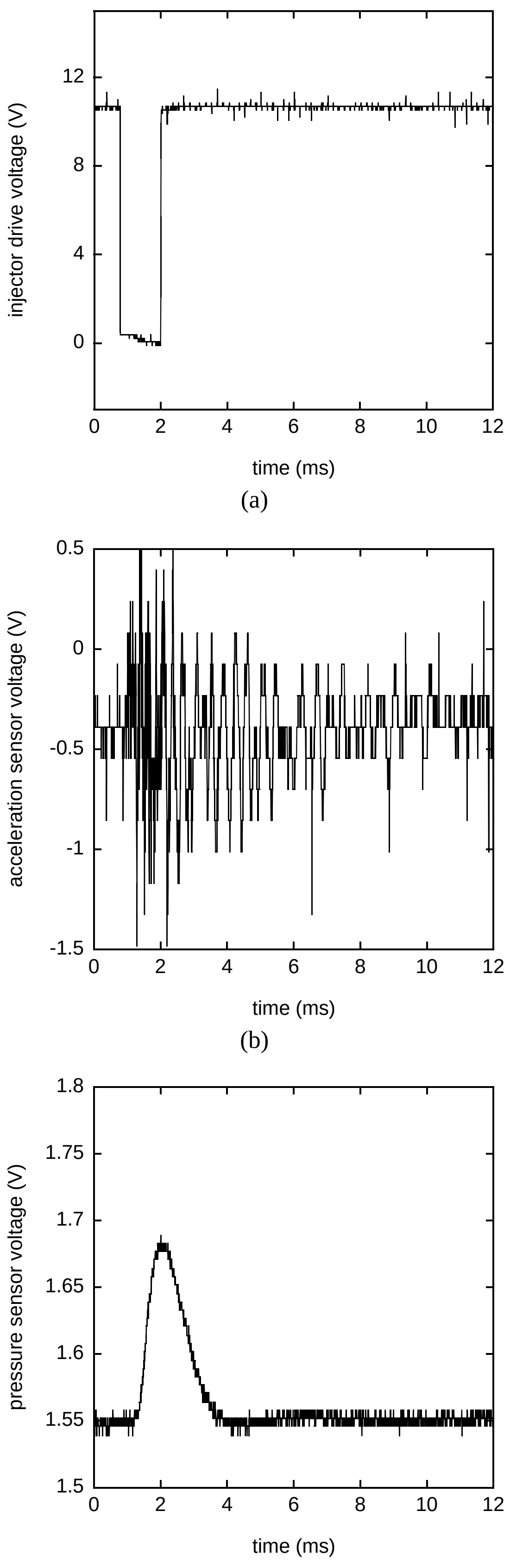


Fig. 2. A schematic diagram of the experimental setup to measure the injection rate with the Bosch method and the injection timing with the accelerometer

The measurement process of both the fuel injection rate by the Bosch method and the needle lift or return timing by the accelerometer can be summarized as follows. To eliminate the back-pressure wave that arises due to the fuel injection, a brass tube is filled with fuel and its back pressure is regulated by the pressure control valve. Fuel is then injected into the brass tube, and the pressure wave induced by the fuel injection is detected using a

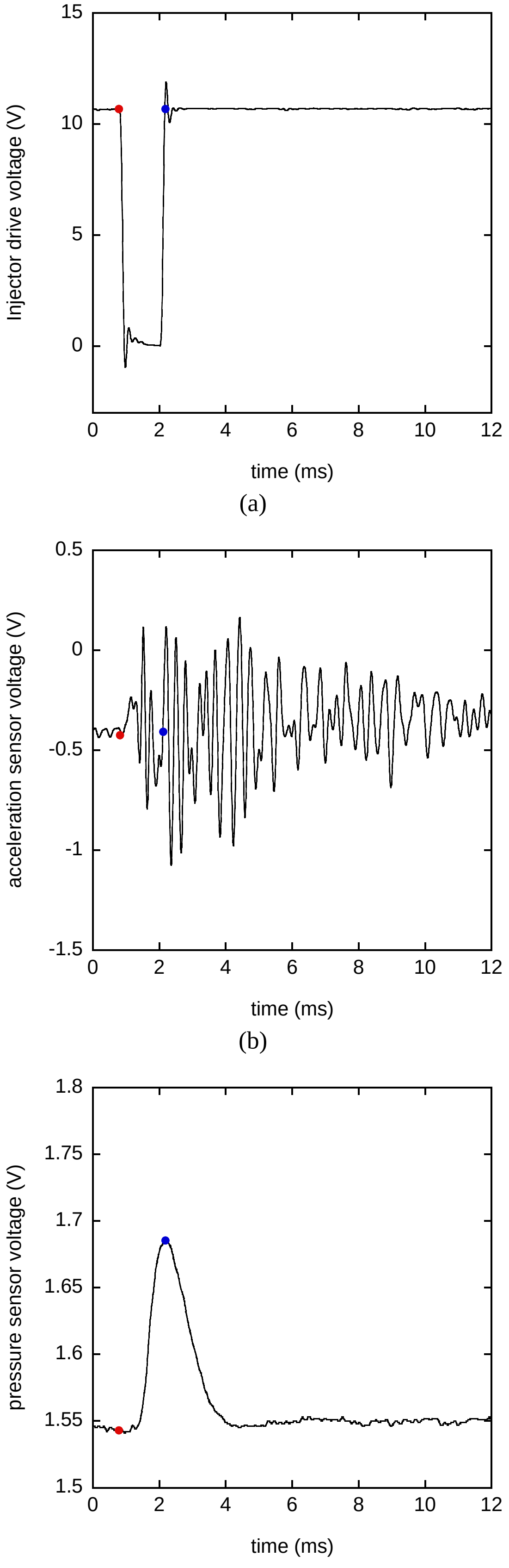


(a)

(b)

(c)

Fig. 3. Original experimental results recorded with a single injection: (a) the injector driving voltage, (b) the pressure sensor voltage, and (c) the acceleration sensor voltage

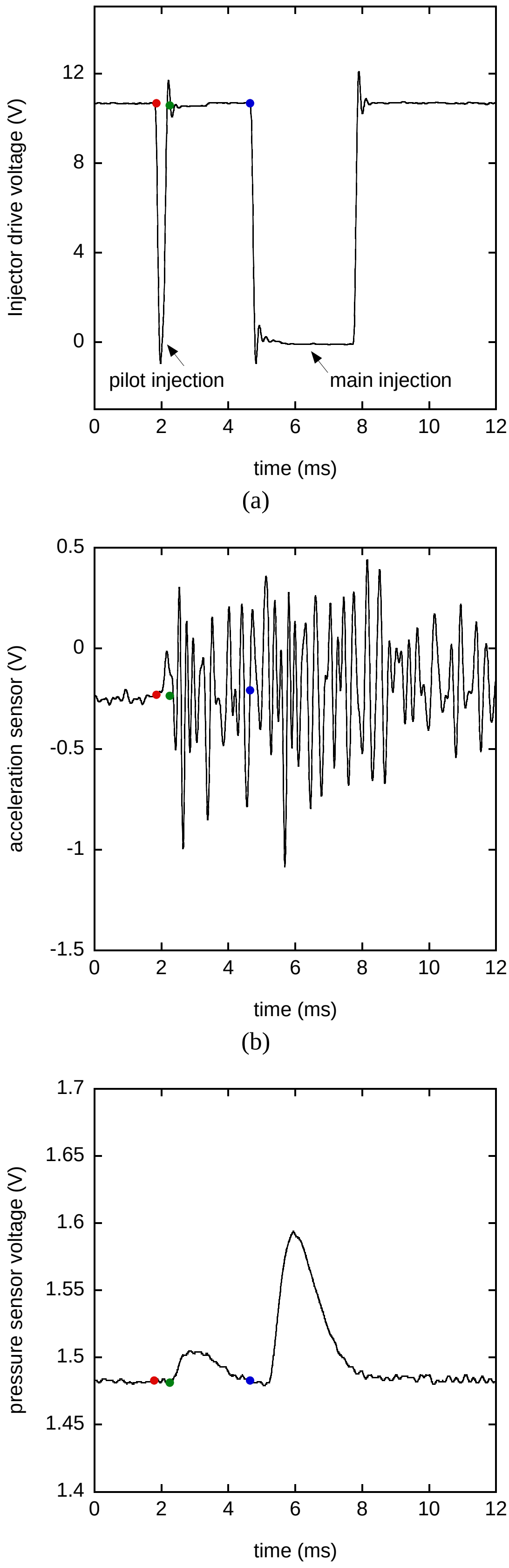


(a)

(b)

(c)

Fig. 4. Low-pass filtered experimental results with the single injection pattern:(a) the injector driving voltage, (b)the pressure sensor voltage, and (c) the acceleration sensor voltage

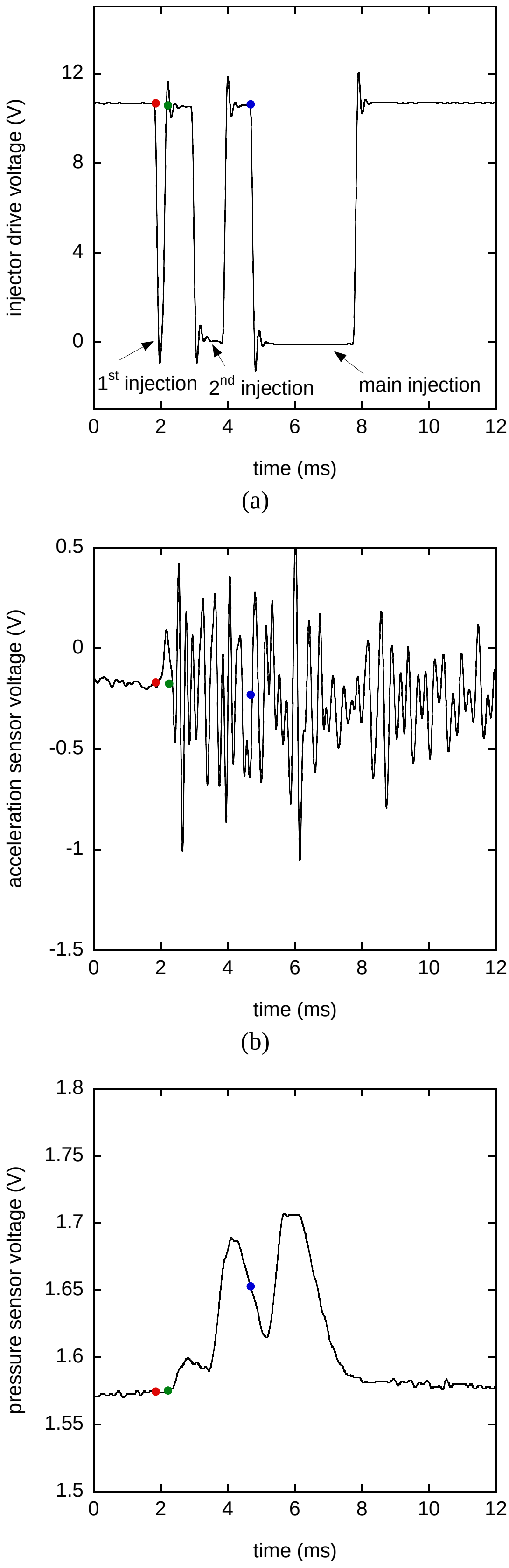


(a)

(b)

(c)

Fig. 5. Low-pass filtered experimental results with the pilot- and the main- injection pattern: (a) the injector driving voltage, (b) the pressure sensor voltage, and (c) the acceleration sensor voltage



(a)

(b)

(c)

Fig. 6 Low-pass filtered experimental results with the triple-injection pattern: (a) the injector driving voltage, (b) the pressure sensor voltage, and (c)the acceleration sensor voltage piezo-electric pressure sensor and recorded onto a digital oscilloscope. Simultaneously, the accelerometer attached to the outside of the injector records the impact wave caused by the needle when it is lifted and later returns. This fuel injection process is repeated thousands of times, and the amount of injected fuel is then measured, from which the average fuel injection rate by a single injection can be calculated. With this data, the fuel pressure sensor signals can be matched to the time-resolved fuel injection rate. Diesel fuel was used for the experiment, and the injection pressure was set to 120MPa. The fuel injection patterns used in the experiment were the single-injection, pilot-injection, and triple-injection patterns.

III.RESULTS AND DISCUSSION

With the common rail pressure kept at 120MPa, the injector is activated as a single-injection pattern. Fig. 3(a) shows the injector driving voltage signal. The injector is actuated by switching on the injector driving voltage. At a time of 0.6 ms, as shown in Fig. 3(a), the injector is activated by switching on the injector driving voltage. The activation of the solenoid in the injector causes the needle to overcome the spring force which is pushing it down, resulting in fuel injection with the lifting of the needle. The injector is deactivated at a time of 2.1 ms, which stops the fuel injection process, with the needle returning to its initial position. The spring force immediately presses the needle down as the force pushing up the needle disappears. Thus, the fuel injection signal duration with the single-injection pattern is 1.5 ms. Fig. 3(b) shows the acceleration sensor voltage with time. The acceleration sensor detects the impact to the injector holder caused by the needle lift instantly. The acceleration sensor voltage oscillated instantly with the needle impact onto the nozzle holder. Fig. 3 (c) shows the pressure wave signal measured by the piezo-electric pressure sensor with the experimental setup described in Fig. 2. The pressure wave signal is caused by the fuel injection into the fluid which filled the brass tube as shown Fig. 2. With the single injection condition, the injector driving voltage, pressure sensor voltage, and acceleration sensor voltage according to time were recorded simultaneously using the digital oscilloscope. These results are presented in Figs. 3(a), 3(b), and 3(c), respectively.

Figs. 3(a), 3(b) and 3(c) show that there is considerable noise in the recorded data. To eliminate the noises, the raw data of Figs. 3(a), 3(b), and 3(c) were processed using a low-pass filter. LabView® Software was used for the low-pass filtering process. The processed results corresponding to Figs. 3(a), 3(b), and 3(c) are shown in Figs. 4(a), 4(b), and 4(c), respectively. As is evident, the graphs without noise are much clearer.

In Fig. 4(a), the red solid circle is used to mark the fuel injection start signal. The same red solid circles are also marked in both Figs. 4(b) and (c) with the times synchronized to the red circle in Fig. 4(a). Referring to Fig. 4(b) and comparing it to the injector driver signal in Fig. 4(a), it can be seen that the red solid circle point where the injector activation is started is completely synchronized to the point where the acceleration sensor voltage suddenly increases. This result indicates that the acceleration sensor can accurately detect the instant the needle is lifted. However, the red solid circle where the injector is starting to activate does not indicate the actual fuel injection start. In general, the fuel injection starts with a time delay after the injector driving voltage signal is supplied to the injector. The red solid circle in Fig. 4c of the pressure sensor signal curve is not precisely synchronized with timing of the injector driving voltage signal. The pressure sensor voltage starts to increase a slightly later than the time at the red solid circle (henceforth called the ‘injector time lag’). The pressure sensor voltage is completely coupled to the actual fuel injection rate. The actual fuel injection occurred a little later than the time at the red solid circle. The pressure sensor signal could detect the needle lift instance by considering the ‘injector time lag’ which is generally supplied by automotive parts makers.

With regard to marking the end timing of the fuel injection, the blue solid circle shown in Fig. 4 denotes this. In Fig. 4(a) the blue solid circle marks the timing of injector deactivation by the switching off of the injector driving voltage. Fig. 4(b) shows that the acceleration sensor voltage drastically increases around the blue solid circle with the injector drive voltage switching off. Thus, with the single-injection pattern, the acceleration sensor can pinpoint the end time of injector deactivation or when the needle returns to its original position. The blue solid circle in Fig. 4(c) is located at an arbitrary point on the pressure sensor signal curve. The pressure sensor cannot pinpoint the instance of injector deactivation. Although the injector is deactivated at the blue solid circle time of 2.1 ms, the fuel injection continued to nearly 4.0 ms, as shown in Fig. 4(c)

Figs. 5(a), 5(b), and 5(c) show the injector driving voltage, pressure sensor voltage, and acceleration sensor voltage, respectively, when the fuel is injected with the pilot and main injection pattern. Fuel was injected in two stages: the first pilot injection duration was approximately 0.1 ms and the second main injection lasted 1.8 ms, as shown in Fig. 5(a). Fig. 5(b) shows that acceleration sensor signal can catch the needle lift and return timing with the pilot injection. However, Fig. 5(c) shows that the pressure sensor clearly cannot pinpoint the needle lift and return timing with the pilot injection. The blue solid circle in Fig. 5(a) represents the start of injector activation for the main injection. The needle lift and return with the main injection stage cannot be captured with either the acceleration or the pressure sensor signals, as shown in Figs 5(a) and 5(b).

Figs. 6(a), 6(b), and 6(c) are graphs of the injector driving voltage, the pressure sensor voltage, and the acceleration sensor voltage when the injector was activated in three stages, which consist of the first injection, the second injection, and the main injection. In Fig. 6(a), the red and green solid circles represent the needle lift and return of the injector with the first injection stage. Fig. 6(b) shows that the acceleration sensor signal catches the needle lift and return of the injector with the first injection. However, the pressure sensor signal in Fig. 6(c) cannot pinpoint the needle lift and return of the injector with the first injection. The needle lift and return of the injector related to the second injection and the main injection activation cannot be detected by analyzing the acceleration and pressure sensor signals.

IV. CONCLUSION

The fuel injection rate shape of a common rail diesel injector was obtained using the Bosch method. An accelerometer was attached onto the outside of the injector and was used to catch the needle lift and return of the injector. Various patterns (single-injection, pilot-injection, triple-injection) were tested, and the signals from the sensors were analyzed, yielding the following results.

(1) With a single injection, the accelerometer attached to the injector accurately caught the needle lift and return of the injector.

(2) For injection patterns with multiple injections, in this case the pilot and triple injections, the needle lift and return of the injector at the stage of pilot injection were accurately detected with the acceleration sensor, whereas those of the second and third injections were unidentifiable.

(3) The injection rate shapes with the Bosch method can also accurately capture the needle lift and return of the injector at the first injection stage, but it cannot identify the needle lift and return of the injector at all the second and the main injection stage.

REFERENCES

[1] B. Fulton and L. Leviticus, Variable Injection Timing Effects on the Performance and Emissions of a Direct Injection Diesel Engine Brien Fulton and Louis Leviticus. SAE paper, 932385, 1993.

[2] K. P. Nandha and J. Abraham, Dependence of Fuel-Air Mixing Characteristics on Injection Timing in an Early-Injection Diesel Engine. SAE Paper 2002-01-0944, 2002.

[3] Diesel engine management .

[4] A. Vanegas, H. Won, C. Felsch, M. Gauding, and N. Peters, Experimental investigation of the effect of multiple injections on pollutant formation in a common-rail DI diesel engine. SAE paper, 2008-01-1191, 2008.

[5] R. Matsui, K. Shimoyama, S. Nonaka, I. Chiba, and S. Hidaka, Development of high-performance diesel engine compliant with Euro-V. SAE paper, 2008-01-1198, 2008.

[6] Y. Hotta, M. Inayoshi, K. Nakakita, K. Fujiwara, I. Sakata, Achieving Lower Exhaust Emissions and Better Performance in an HSDI Diesel Engine with Multiple Injection. SAE paper No. 2005-01-0928, 2005.

[7] M. Badami, F. Mallamo, F. Millo, E. E. Rossi, Influence of Multiple Injection Strategies on Emissions, Combustion Noise and BSFC of a DI Common Rail Diesel Engine. SAE Paper No. 2002-01-0503, 2002.

[8] T. Fang, R. E. Coverdill, C. F. Lee, R. A. White, Low Temperature Combustion within a Small Bore High Speed Direct Injection (HSDI) Diesel Engine. SAE paper No. 2005-01-0919, 2005.

[9] W. Zeuch: Neue Verfahren zur Messung des Einspritzgesetzesund Einspritz-Regelmassigkeit von Diesel-Einspritz-pumpen, MZT, Jahr. 22 Heft 9, 1961.

[10] W. Bosch: The Fuel Rate Indicator: A New Measuring Instrument for Display of the Characteristics of Individual Injection, SAE Paper 660749,1966.

[11] M. Marcic, A New Method for Measuring Fuel-Injection Rate SAE paper 980804.

[12] M. Marcic, Measuring the Injection Rate in Diesel Multi-Hole Nozzles, SAE paper 901670.