

## Investigation of the Internal Dynamics of Diesel Nozzles by Time-Resolved Laser Doppler Vibrometry

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### Abstract

Experimental and numerical data show that high frequency pressure fluctuations and vibrations exist inside modern diesel injectors. Even though nozzle vibrations may influence the shape and stability of sprays, no thorough spectral investigations have been reported and limited data are available. Experiments were performed to measure time-resolved vibration spectra of diesel injector nozzles using three dimensional laser vibrometry, needle lift sensor and fuel pressure transducer. The vibrometer, which measures the velocity of a vibrating object using the Doppler effect, was used to scan injector nozzle tips during the injection event. In order to allow a comparative investigation of the effect of nozzle type and orifice diameter, the nozzle library included custom-built single-orifice nozzles with VCO and minisac geometries. All nozzles were tested at injection pressures ranging from 60 to 140 MPa. A spectral peak was found around 7 kHz for all nozzles and every injection pressure. Further evidence of a similar frequency was obtained from the pressure sensor and injector needle lift sensor. This frequency is proposed to be caused by the injector's needle oscillation in the axial direction. Other spectral peaks were found between 35 and 45 kHz, suggesting that these particular frequencies may be linked to nozzle dependent cavitation phenomena. For the 200  $\mu\text{m}$  nozzle orifices, these oscillations were found to progressively extend into the steady state injection period as the injection pressure was increased. This was suggested to be an indication of the presence of quasi cyclic cavitation inside the orifices.

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### Introduction

The importance of fuel atomisation is well recognized and has been extensively studied experimentally and theoretically. It is generally accepted that a key factor in simulating engine combustion processes is the accurate modelling of the interaction between injector nozzle, fuel sprays and in-cylinder flows. The complexity of the processes involved in the injection of diesel fuels is such that many facets involved are still not well understood. Obtaining direct information on the injector's internal fuel flow is particularly challenging due to the small scale of the mechanical design and high flow velocities and pressures. Researchers often resort to applying non-intrusive optical diagnostic techniques onto specially modified or enlarged nozzles, in order to study internal flows and cavitation processes [1,2].

There is some experimental and numerical evidence that high frequency pressure fluctuations exist inside modern diesel injectors, and that they influence the shape and stability of the sprays [3-5]. These pressure fluctuations are usually recorded using sensors fitted to the common-rail or close to the injector. Although these measurements provide insightful information, frequency damping and potentially supersonic flow conditions may conceal the link between pressure fluctuations and nozzle cavitation.

The authors previously reported on the observation of high frequency oscillations in needle lift traces, and near-nozzle diesel jet [6]. Oscillations of the injector needle in the axial direction were observed, and proposed to lead to transversal oscillations of the liquid fuel jet at approximately 7 kHz. These oscillations were suggested to contribute to the formation of slugs of fuel which were seen detaching from the spray.

In order to investigate the nature and source of needle oscillations and pressure fluctuations further, an experiment was devised to measure the vibration of the injector tip throughout the injection event, for a range of injection pressures and nozzle geometries. The authors believe that the direct and time-resolved measurement of diesel nozzle vibration in three dimensions is both novel and unreported, and could lead to further insight into the internal dynamics of the injector's mechanical part and fuel flow.

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## Experimental Methods

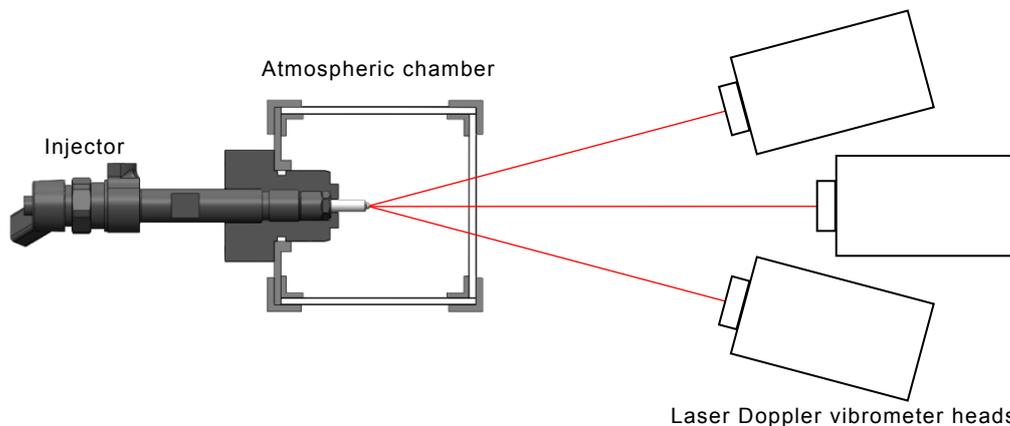
In order to provide a sufficiently large optical access, and to minimise the complexity of the experiment, the injections were performed in a static enclosure at atmospheric conditions. The assumption that ambient gas pressure and temperature have a negligible effect on the vibration of the injectors was deemed reasonable. The fuel injection equipment (FIE) consisted of a second generation Bosch common-rail capable of achieving injection pressures of 160MPa. It comprised a low pressure pre-supply pump, a fuel filter, a CP1 high-pressure pump connected to the common rail, and an injector with interchangeable nozzles. The CP1 pump was a three-plunger radial-piston pump, operated at a constant speed of 2820 rpm. The common rail was fitted with a pressure sensor and regulated by a pressure regulator valve. The high-pressure fuel line was instrumented with a Kistler 4067 piezoresistive high-pressure transducer. A current clamp was used to record the instantaneous current drawn by the injector. The high-pressure pump and injector were controlled by a purpose-built controller and software which allowed independent control of the injection pressure and timing. The controller allowed triggering the injection event and acquisition chain independently.

The fuel injector studied with the vibrometer was a production Bosh CR2 electro-magnetic actuated common rail injector. The injector nozzles were interchangeable and therefore allowed testing of different nozzle types and nozzle orifice diameters. A second identical injector was specially equipped with a needle plunger lift sensor to obtain a time-resolved position of the needle during the injection. Needle lift traces were recorded for all nozzle types and for a range of injection pressures. In order to allow a comparative investigation of the effect of nozzle type and orifice diameter, the nozzle library included 8 custom-built single-orifice nozzles with different geometries. The full test matrix is provided in Table 1, and includes 8 nozzles and 6 injection pressures, with a total of 48 individual test points.

**Table 1 Nozzle library and test matrix for the laser Doppler vibrometry measurements**

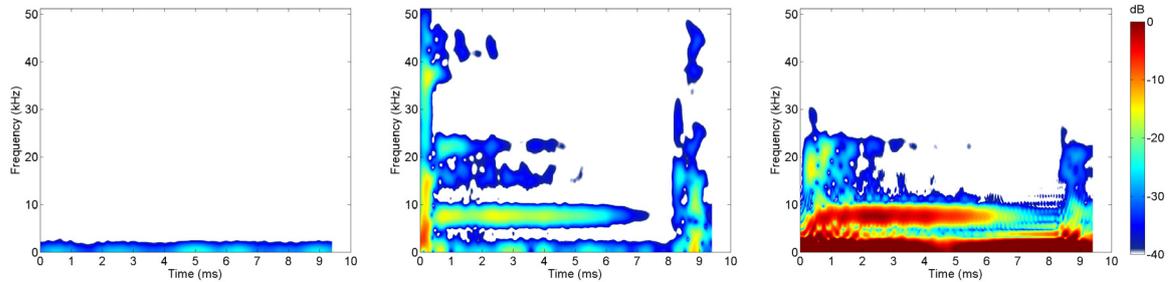
Nozzle type	Orifice diameters ( $\mu\text{m}$ )	Injection pressures (MPa)
VCO	100; 200	60; 100; 140
Minisac	100; 160; 200	60; 100; 140

The laser Doppler vibrometer (LDV) was a Polytec PSV-400-3D Scanning Vibrometer, composed of three separate laser heads. In order to find the optimum spatial location on the nozzle tip for the LDV measurements, 9 locations were probed. Measurements were repeated 30 times to obtain statistically representative spectra. The spectra obtained for the 9 spatial locations had similar peak frequencies, but the signal-to-noise ratio was the highest on the tip of the injector's nozzle. This indicates that the nozzle vibrated homogeneously and that the collection efficiency of the LDV was the highest when probing the nozzle's flat tip, which offered a more favourable scattering angle.



**Figure 1** Schematic of the experimental configuration for the time-resolved 3D laser Doppler vibrometry on the atmospheric chamber.

For each test point listed in Table 1, a spatial calibration of the LDV system was performed before 5 LDV measurements were made. The vibrometer was also set to record the instantaneous fuel line pressure and current drawn by the injector. Unless otherwise mentioned, all spectrograms shown were computed using the average of 5 consecutive measurements. Since the hydraulic state of the injector was uncertain when starting the FIE, the very first injection of fuel was never recorded. The injection duration was kept constant at 8 ms for all test points. This extended injection duration was used intentionally to facilitate the analysis of the steady state part of the injection separately from the transient phases linked with the needle opening and closure.



**Figure 2** Averaged spectrograms for a VCO 200  $\mu\text{m}$  single-hole nozzle obtained by laser Doppler vibrometry without (left) and with (centre) fuel injection at 140 MPa pressure, and from the high-pressure fuel transducer (right).

In order to have a full control over the data analysis, the raw measurements were exported and processed using bespoke software. The vibrometer used in this study was able to measure 1024 spatial displacements over a time period of 10 ms. This represents time steps of  $9.766 \mu\text{s}$ , which meant that the highest frequency which could be resolved by discrete Fourier transform was 51.2 kHz, with a resolution of 100 Hz. In order to observe the evolution of the vibration spectrum throughout the injection event, spectrograms were produced using a discrete short-time Fourier transform. Each block of 1024 LDV data points was divided into 8 segments of 128 points and a sliding FFT was applied. The continuous spectrograms allow to differentiate the frequencies which are specific to the needle opening and closing phases, from those that are observed throughout the injection event, as can be seen in Figure 2.

Although care was taken to minimise potential sources of interference, a number of cyclic and random phenomena could still deteriorate or interfere with the measurement of the spectral density of the nozzle tip. Since the frequency and amplitude of the nozzle vibration were obtained by measuring the Doppler shift of 3 laser beams focused on the nozzle tip, any spurious back scattering or beam steering could deteriorate the measurements. The presence of atomised fuel inside the static enclosure was indeed found to significantly interfere with the LDV measurements. This was established to be due to random light scattering by diesel droplets, and refraction of the laser beams by fuel deposited on the front window of the static enclosure. This issue was eliminated by capturing the spray with a cylindrical pipe positioned downstream of the nozzle, and regularly cleaning the static enclosure's front window.

The common-rail system included several rotating and vibrating components which were expected to contribute to the power spectrum recorded by the LDV. A characterisation of these components was required so that the injector's contribution to the spectral density could be obtained. The first rotating component in the injection system was the low pressure pre-supply pump which drew fuel from the tank. The high-pressure pump was a Bosch CP1 pump with a three-plunger radial-piston design, driven by an electric motor at a constant speed of 2820 rpm. It could be inferred that the motor introduced a contribution in the spectral density at 47 Hz, and the pump at 141 Hz. The third vibrating component in the injection system was the common-rail's pressure regulator valve, which was operated at 1.0 kHz.

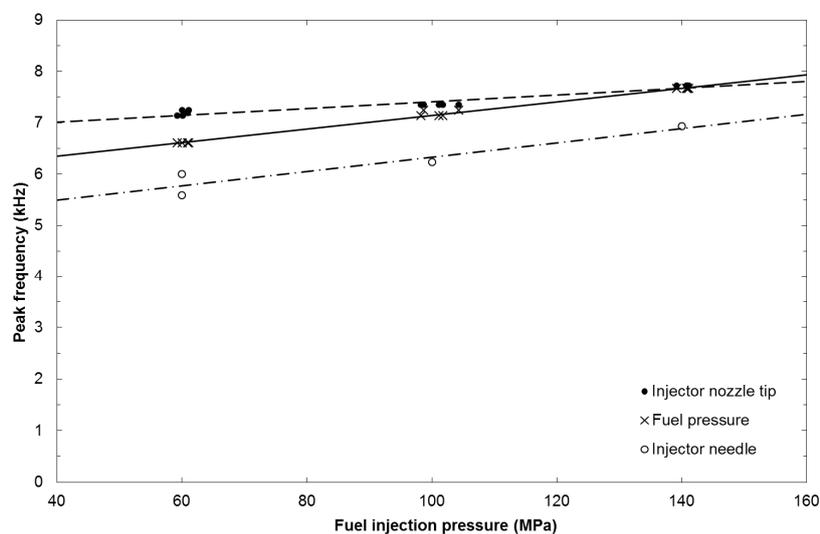
In order to reduce the transmission of vibration from the pre-supply and high-pressure pumps, the injection system and static enclosure were mounted on separate tables with damped legs. The only rigid connection between these two tables was the high-pressure fuel line which linked the common-rail to the injector. The vibrations transmitted from the fuel pumps and ancillary equipments to the injector were characterised by recording baseline measurements. These were conducted by recording the vibration spectrum of the injector nozzle with the test bed in normal operation, but with no injection trigger pulse. This was repeated 5 times for every injection pressure, and the measurements averaged to produce baseline spectrograms such as the one shown in Figure 2.

## Results and Discussion

The spectrograms presented in Figure 4 are averages of 5 individual measurements, taken for injection pressures of 60, 100, and 140 MPa. For each pressure condition 3 spectrograms are shown in order to decouple the effects of the mechanical and fluidic vibrations.

The total vibration of the nozzle tip measured by the LDV can be categorised into three types: background parasitic noise, injector's mechanical operation, nozzle cavitation. In order to characterise the background parasitic noise generated by the ancillaries, spectrograms were recorded with the test bed in normal operation, but without fuel injection. Care was taken to ensure that all equipment and instrumentation of the test bed were in normal operation, with the exception of the injection trigger pulse which was disabled. These spectrograms are presented in the left column of Figure 4 and show that no significant vibration was recorded, with mild parasitic noise only below 5 kHz.

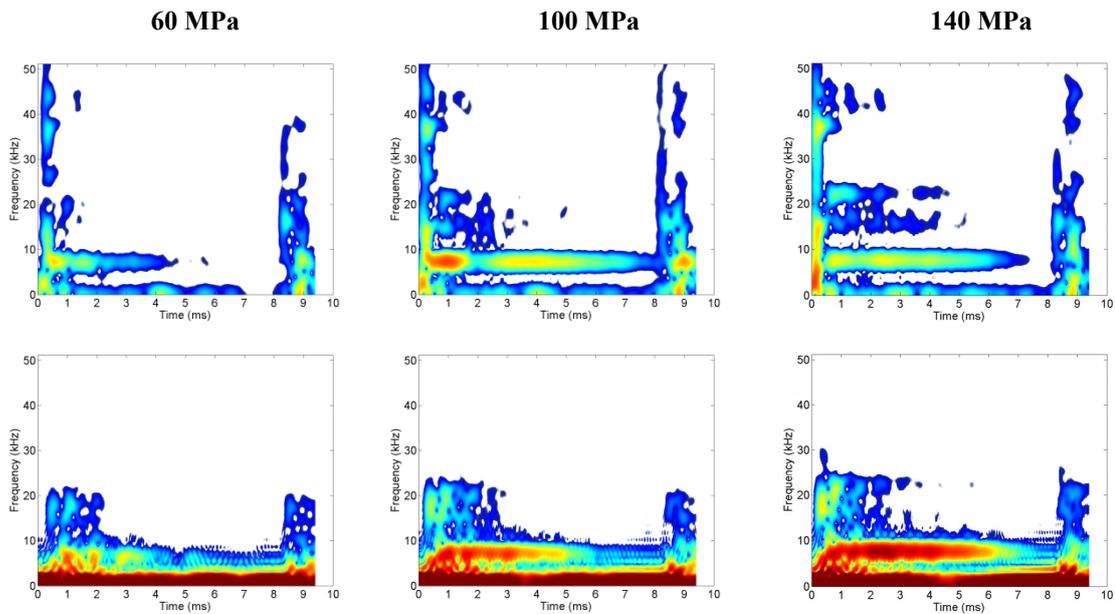
The contribution of the injector's mechanical operation to the spectra can be estimated in several ways. Firstly, the spectral density of the signal measured by the needle plunger lift sensor was used to identify the frequency at which the injector needle oscillates in the axial direction. This frequency was found to be proportional to the injection pressure, and measured between 5.5 and 7.2 kHz for pressures between 60 and 140 MPa (Figure 3). Secondly, the mechanical operation of the injector is known to lead to fuel pressure fluctuations [4]. Hence, computing the spectrograms for the signal measured by the high-pressure transducer directly upstream of the injector gives an indication of the frequencies induced by the mechanical operation of the injector. These are presented in the right column of Figure 4, and the dominant frequency at 7 kHz is in agreement with the frequency obtained independently from the needle lift signal. It can be observed that the mild sensitivity of that frequency to injection pressure (Figure 3) is also consistent with the correlations observed for the needle lift sensor and for the liquid fuel spray oscillations. It can also be noted that the 2<sup>nd</sup> and 3<sup>rd</sup> harmonics of the 7 kHz fundamental frequency are present on some of the spectrograms. These harmonics are more pronounced at 140 MPa, the highest injection pressure tested, with bands visible at 7.5, 15 and 22.5 kHz throughout the injection time. Although the spurious signal resulting from the harmonics may be considered detrimental to the spectral analysis, they are easily detected on the fuel pressure spectrograms and confined to the first 3 harmonics.



**Figure 3** Correlations between injection pressure and 7 kHz oscillation peak frequency shift measured for the injector tip (LDV), fuel pressure (piezoresistive transducer) and injector needle (plunger lift sensor).

The third type of vibration expected to occur during the injection process is caused by cavitation taking place inside the nozzles' orifices. The spectra for nozzle cavitation cannot be measured directly, but it is proposed that they can be inferred by subtracting the pressure transducer spectrograms from the total nozzle vibration spectrograms shown in the right and central columns of Figure 4, respectively. The fundamental frequency linked to the needle's axial oscillation is visible on the spectrogram, along with the 2<sup>nd</sup> and 3<sup>rd</sup> harmonics at

140 MPa. Interestingly, the spectrograms indicate that significant levels of vibration occur during the first and last 1 ms of the injection period. These time intervals are dominated by the transient processes that take place during the needle opening and closing, suggesting that increased levels of cavitation may occur. This is supported by simulations of transient cavitation processes conducted by Lee and Reitz [7] for the opening and closing phases of diesel injectors. The augmented level of cavitation was particularly noticeable during the closing phase when the fuel flow to the nozzle orifice was throttled by the needle, but the exit mass flow decreased relatively slowly due to inertia, leading to pressure drop inside the orifice. An indication of the presence of cavitation during the steady state regime of the injection can also be noticed at 140 MPa, where a band can be seen to extend into the injection period between 35 and 45 kHz.



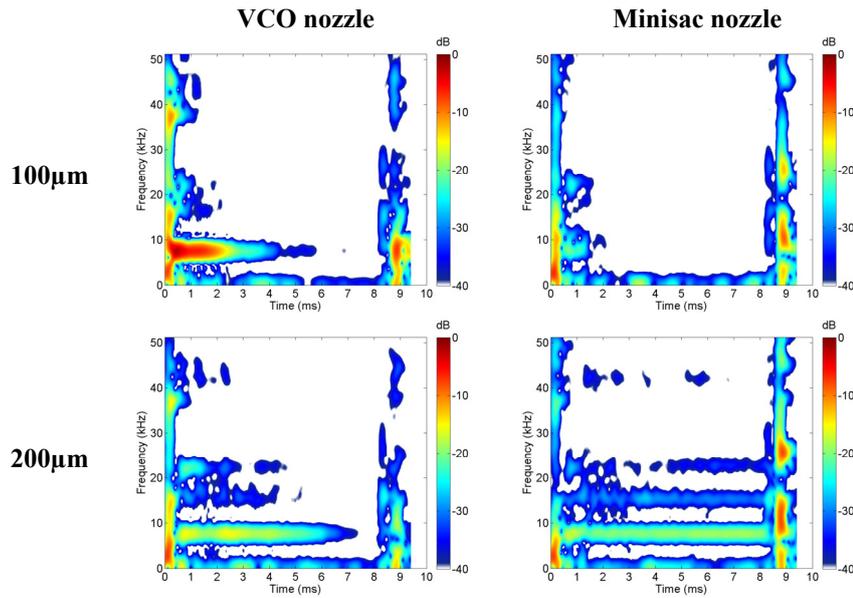
**Figure 4.** Averaged spectrograms showing the vibration spectra of a VCO 200µm single-hole nozzle recorded by LDV (top row), and by the high-pressure fuel transducer (bottom row).

High-speed videos of the near-nozzle spray recorded by the authors [6] using the same injectors, demonstrated cyclic oscillations of the liquid spray. An estimate of the frequency of these oscillations was obtained by calculating the time difference between two frames showing similar spray shape. The frequency was found to be approximately 6.8 kHz for a VCO 200 µm single-hole nozzle with 160 MPa rail pressure, which is consistent with the values reported in Figure 3.

Considering that evidence of a frequency close to 7 kHz was also obtained from the pressure sensor, injector needle lift sensor and nozzle tip vibration, this frequency is proposed to be caused by the injector's needle oscillation. The formation of fuel slugs detaching from the bulk of the liquid spray may be associated to these transversal oscillations, and are likely to favour clustered distributions of soot and inhibit soot oxidation due to the associated local depletion of oxygen [8].

The effect of nozzle geometry on the vibrational properties of the injector was characterised for a range of orifice diameter and nozzle design. Figure 5 shows the spectrograms recorded for VCO and minisac nozzles, with cylindrical orifices of 100 and 200 µm. The minisac nozzles lead to more intense vibrations during the needle closing phase, compared to the VCO nozzles. This may be caused by a pressure drop inside the sac after the needle has closed, leading to more pronounced flow stretching and cavitation. An alternative explanation could be that the water hammer effect caused by the rapid closing of the injector [9] is stronger for minisac nozzles, although estimates suggest that the resulting frequency should be below 20 kHz.

The 35-45 kHz band which was visible in Figure 4 for a VCO nozzle with an injection pressure of 140 MPa can also be observed in Figure 5 for both the VCO and minisac nozzles, although only for the 200 µm orifices. The 100 µm orifices show no evidence of such a frequency band, suggesting that it may be an indication of cavitation inside larger orifices.



**Figure 5.** Spectrograms for single-hole VCO and minisac nozzles, with orifice diameters of 100  $\mu\text{m}$  (top row) and 200  $\mu\text{m}$  (bottom row) recorded for injections with 140 MPa pressure

### Summary and Conclusions

Initial results obtained from the application of three dimensional laser Doppler vibrometry to characterize and diagnose cyclic phenomena inside diesel nozzles seemed promising. The technique enables investigations of cavitation and other cyclic processes inside real-size injectors. It can also be used with real fuels at elevated pressures and does not require physical modifications of the nozzles.

In the present study, spectrograms of diesel injector nozzle tips were obtained during injection events. Compared to the VCO nozzles, the minisac nozzle types exhibited more intense vibrations during the needle closing phase, suggesting higher level of cavitation or water hammer.

An oscillation between 6 and 7.5 kHz was measured using the 3D laser vibrometer, fuel pressure sensor and injector needle lift sensor. This frequency was recorded for all nozzles tested and was found to be proportional to the injection pressure by the four independent instruments. This frequency is proposed to be caused by the injector's needle oscillation in the axial direction and may contribute to the formation of fuel slugs.

Oscillations between 35 and 45 kHz were observed during the needle opening phase. For the 200  $\mu\text{m}$  nozzle orifices, these oscillations were found to progressively extend into the steady state injection period as the injection pressure was increased. This was suggested to indicate the presence of quasi cyclic cavitation.

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