# Noise Reduction in Gasoline DI Engines by Isolating the Fuel System

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## Abstract

We developed a novel method for reducing the noise level associated with the high-pressure fuel system in gasoline direct-injection (DI) engines. We focused on the noise level at idle running speed, because the idle state engine noise is the only noise source to the driver. To reduce the noise level of the idling engine, we focused on the vibration transmission path from the high-pressure fuel system to the cylinder head which results in noise radiation from the engine block. The dominant vibration source of the high-pressure fuel system was fuel pulsation from the high-pressure fuel pump and activation noise of the solenoid-drive injector. To reduce the vibration transmission from the high-pressure fuel system to the cylinder head, the fuel rail and the injector were isolated from the cylinder head by avoiding metal-to-metal contact. This isolation method eliminates the transmission path from the vibration source (high-pressure fuel system) to the radiation source (cylinder head). Mid-frequency noise in the 1 to 3 kHz range is reduced by 5 dB by isolating the fuel rail from the cylinder head with rubber-like damping material. Moreover, high-frequency injector ticking noise above 5 kHz is reduced by 3 dB by suspending the injector from the fuel rail. This method drastically reduces noise radiation associated with high-pressure fuel system in a gasoline DI engine.

## 1 Introduction

Gasoline direct injection (DI) engines have deeply penetrated the gasoline engine market for its benefits of reduction in fuel consumption and increased engine power. However, the noise level of the gasoline DI engine is relatively high compared to that of the conventional gasoline engine.

A schematic diagram of the fuel supply system of a gasoline DI engine is shown in Fig. 1. The high-pressure fuel pump supplies highly pressurized fuel to the injectors. The pressurized fuel is sprayed by the injectors into the combustion chamber. By injecting the fuel directly into the combustion chamber, volumetric efficiency is improved due to the cooling effect of evaporating fuel. Moreover, thermal efficiency is increased due to higher compression ratios provided by the charge cooling effect, which suppresses knocking.

Generally, NVH characteristics are important indexes of vehicle quality, which makes them an important aspect of powertrain development [1]. Moreover, importance of the NVH characteristics is growing not only for luxury vehicles but also for entry-level ones. However, ticking noise from the high-pressure fuel system of gasoline DI engines is more noticeable than that of the typical port fuel injection fuel system of conventional gasoline engines. This is because the higher fuel pressure of the DI engine causes a higher level of vibration force to act on components. For example, intermittent pressurization of the plunger-type high-pressure fuel pump leads to an increase in pressure pulsation amplitude, and this increased pressure pulsation amplitude causes a significant increase in fuel rail vibration. In addition, the higher fuel pressure acting on moving parts, such as valves and plungers, leads to a significant increase in metal-to-metal contact noise.

Typical vehicle noise sources are wind, the transmission, engine, intake/exhaust system and tire-road contact. When a vehicle is travelling, wind becomes the dominant source of vehicle-interior noise. However, in the idle state, the engine is the only source for vehicle-interior noise, because there is no wind noise, no transmission noise and no tire-road noise. Additionally, a driver or passenger sometimes opens a side window or exits a vehicle in an idle state and perceives engine sound directly from the engine bonnet. In such situations, ticking noise from the high-pressure fuel system of gasoline DI engines is quite noticeable. This noticeable ticking noise can reduce vehicle quality and customer satisfaction. Therefore, we focused on reducing noise associated with the high-pressure fuel system of gasoline DI engine in an idle state.

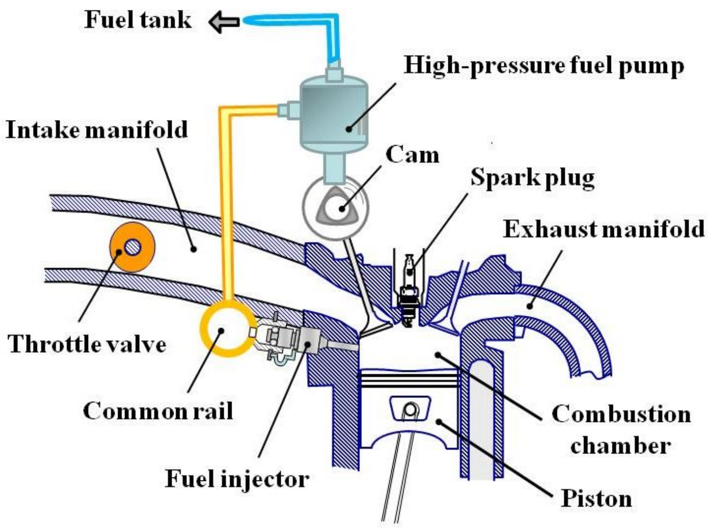



**Figure 1. High pressure fuel system for gasoline DI engine**

## 2 Sound generating mechanisms

The main noise sources of gasoline DI engines are the camshaft/crankshaft, combustion pressure, and the high-pressure fuel system. At idle running speed, noise related to the high-pressure fuel system is more noticeable than camshaft/crankshaft-related mechanical noise and combustion noise due to lower engine speed and lower power output. Therefore, reducing the noise level of gasoline DI engines is important.

Figure 2 shows a schematic representation of the sound generating mechanism of the high-pressure fuel system. Components, such as the high-pressure pump, injector, and rail, are not only noise radiation sources, but also serve as vibration transmission paths to the cylinder head.

Figure 3 shows an outline of the vibration sources, parts, paths, and speakers. The high-pressure pump and injector are considered to be the main vibration sources. The vibration is caused by mechanical contact of valves and by pressure pulsation due to intermittent activation of the high-pressure pump and injectors. This vibration is partially converted into radiation noise from those vibration sources and is partially transmitted to the engine block. This vibration transmitted to the engine block is converted into radiation noise from the engine block. Therefore, both the radiation noise level from the high-pressure fuel system and the vibration level transmitted to the engine block need to be reduced for engine noise

Regarding noise reduction of the high-pressure fuel pump, it has been shown that introducing normal-close flow rate control valve can reduce impact noise at valve openings [3]. In this paper, we focused on reducing the level of vibration transmission from the source to the speaker.

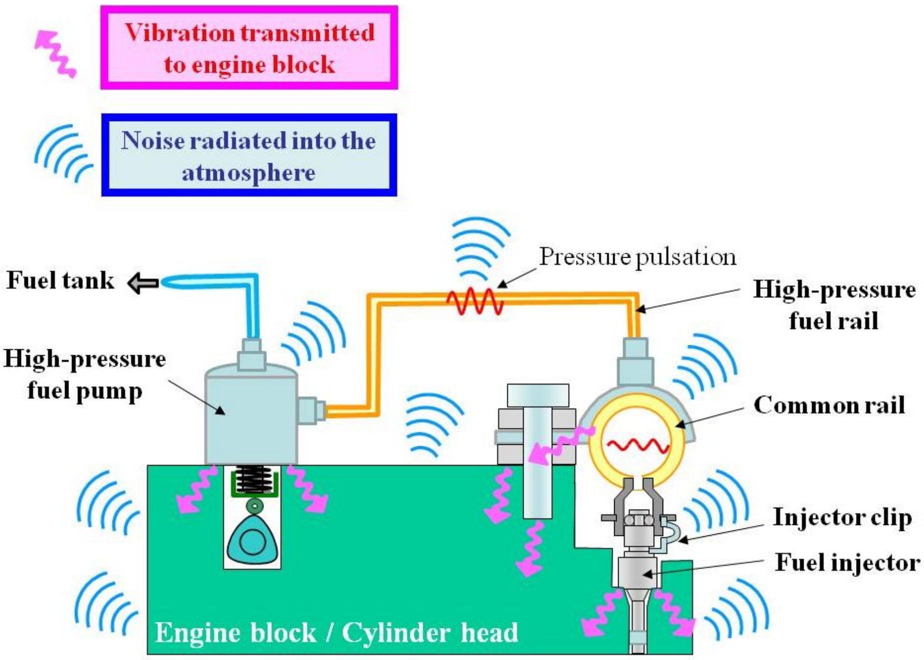



**Figure 2. Schematic representation of vibration/noise generation mechanism for conventional high-pressure fuel system**

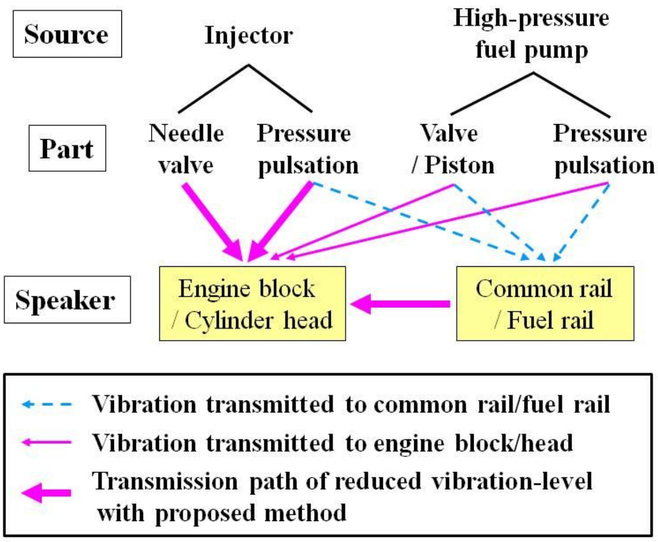



**Figure 3. Outline of vibration sources, parts, paths, and speakers**

# 3 Proposed method

The concept of the proposed method for reducing radiation noise from DI engines is to eliminate the vibration transmission path from the vibration source to the noise radiating speaker; that is, the transmission path from the high-pressure fuel system to the engine block. As shown in Fig. 3, the high-pressure fuel pump and injector are the vibration sources, and the transmission paths from the source to the engine block are the high-pressure fuel pump, common rail, and injector. Our proposed method eliminates two of these three vibration transmission paths, the injector and common rail. Our-two ideas for eliminating the transmission paths are called respectively "fuel injector suspension" and "common rail isolation" as shown in Fig. 4.

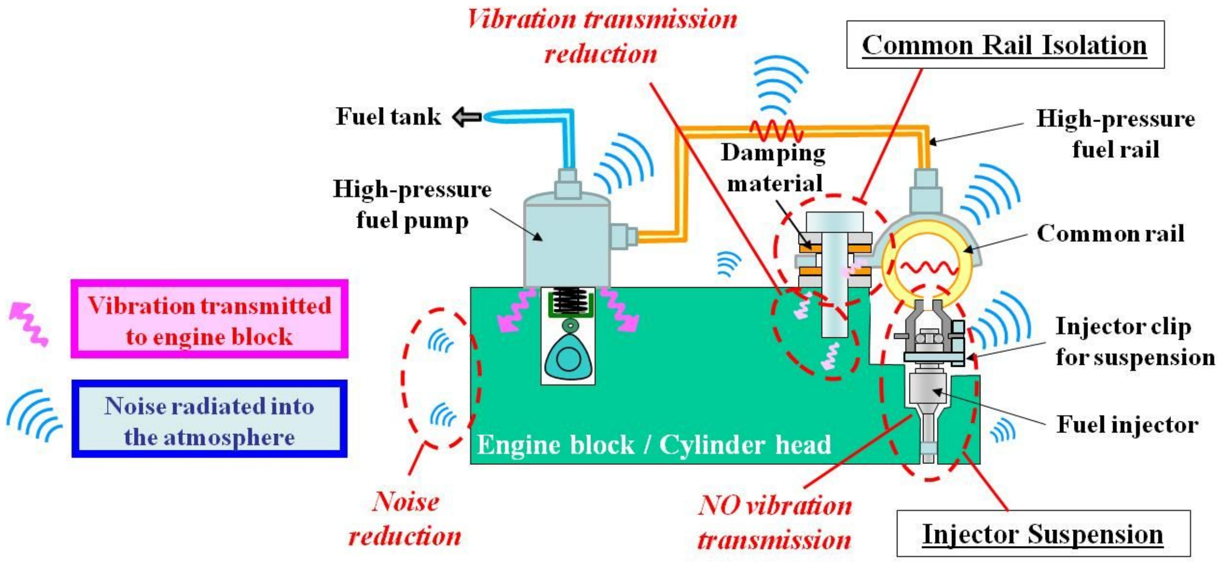



**Figure 4. Schematic representation of concept of the proposed high-pressure fuel system**

Fuel injector suspension means that the fuel injector is suspended from the common rail and contact with the cylinder head is avoided. The only point of contact between the fuel injector and cylinder head is the resin tip that seals the small gap between the fuel injector and combustion chamber. Common rail isolation means that the common rail is fixed to the cylinder head via damping material to reduce the level of vibration transmission from the high-pressure fuel system to the cylinder head.

Regarding injector fixing methods, we examined several methods considering their noise reduction effect, durability, reliability, and cost as shown in Fig. 5. Most current mass production DI engines adopt a metal contact method where the injector sits directly on the cylinder head. The metal contact method is more reliable and less expensive than other methods, but the noise level is higher. Recently, the isolator method for has been used in DI engines to reduce the noise level. The concept is to place a metal or non-metal-isolator between the injector and cylinder head to attenuate vibration transmission.

This approach has a noise reduction effect, especially with a non-metal-isolator, which has a stronger damping effect than a metal one. The disadvantages of the isolator method are higher cost and lower reliability, especially when the isolator is made of rubber, generally has low durability.

On the other hand, with the proposed suspension method, as mentioned above, the only contact point between injector and cylinder is at the resin tip seal (Fig. 4). The suspension method is therefore expected to reduce the radiation noise level drastically because it completely eliminates the vibration transmission path from the high-pressure fuel system to the engine head. From the reliability stand point, injector-clip strength has to be considered carefully because the clip suspends the injector withstand the downward force due to the high-pressure fuel. We have confirmed the reliability of the clip by means of an FEM analysis and experimental measurements.

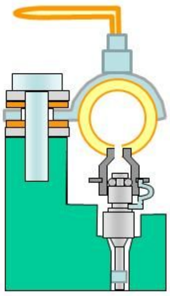
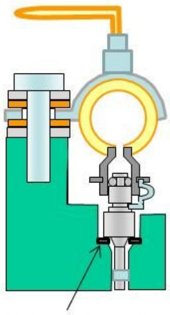
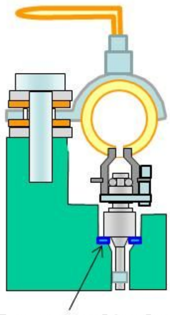
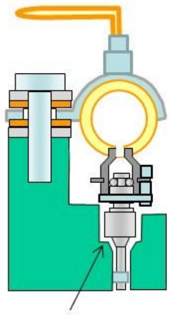
| | Metal contact | Metal isolator | Non-metal isolator | Suspension (proposed) |
|---|---|---|---|---|
| Injector isolation method |  |   |   |   |
| Noise reduction | Base line | + | ++ | ++++ |
| Durability | Base line | Same as base line | -- | Same as base line |
| Reliability | Base line | - | -- | - |
| Cost | Base line | - | -- | - |

**Figure 5. Comparison of injector fixing methods**

## 4 Results

A schematic diagram of the proposed high-pressure fuel system is shown in Fig. 6. This high-pressure fuel system is designed for V6 engines. The injector is suspended from the common rail and the common rail is isolated with a damping material to reduce vibration transmission from the high-pressure fuel system to the engine block.

The testing setup for measuring the sound pressure level (SPL) of the DI engine is shown in Fig. 7. A V6 engine was modified for spin-rig testing to measure engine noise radiation only associated with the high-pressure fuel system; that is, there is no combustion-associated noise. A DC motor drove a one of two camshafts, which drove the high-pressure fuel pump. Neither the crankshaft nor the other camshaft was connected to the motor-driven camshaft, so there was no mechanical noise related-to the crankshaft, pistons and chains.

For sound measurements, four microphones (PCB, 377B02 with preamplifier 426E01) were located around the engine 1m from the engine surface, as shown in Fig. 7. Several pieces of equipment in the measurement chamber, such as the DC motor and fuel-tank pump, were covered with soundproof material to minimize their contribution to sound pressure level as a background noise. The background noise level was lower than the engine noise level by 10 dB or more.

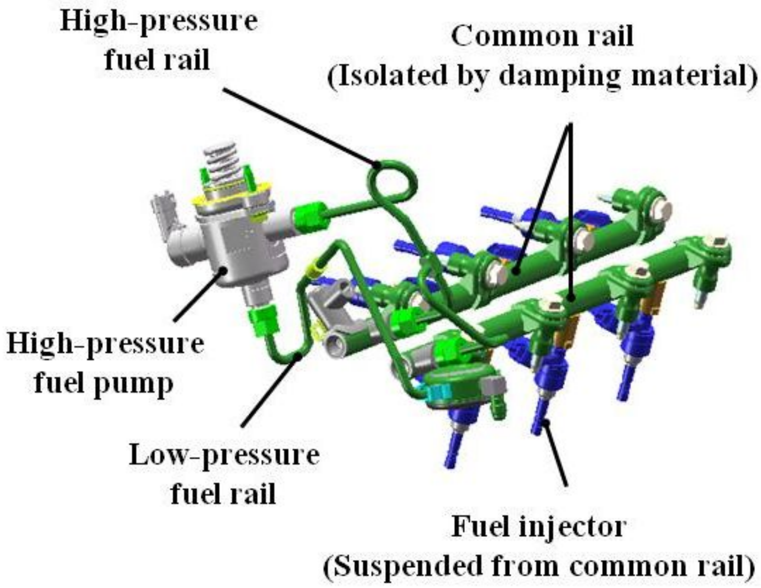
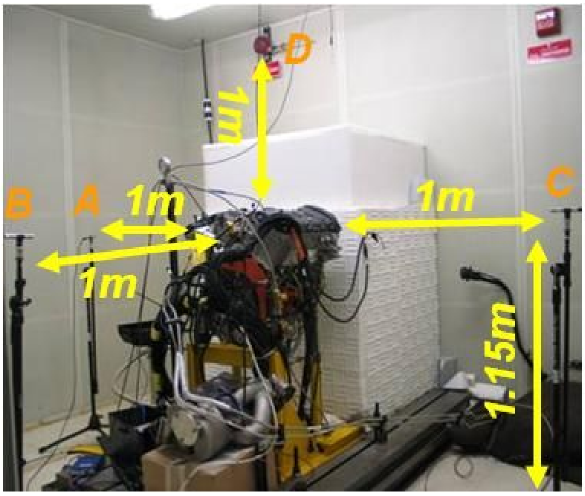



**Figure 6. Proposed high-pressure fuel system**




- Engine: V6 (Spin-rig)
- Drive: Motor-driven camshaft
- Mic.: Four microphones (A, B, C, D)

Figure 7. Testing setup

The noise reduction effect of different common-rail isolation materials is shown in Fig. 8. This result shows the noise reduction effect compared to conventional common-rail fixing method at 1.6 kHz in the third-octave band. As a common-rail isolator, we tested laminated steel, spring washer, and rubber. Laminated steel consists of multiple layer of steel sandwiching damping material between for attenuation of vibration transmission level. The spring washer isn't as rigid as steel block, so it has a potential to reduce the vibration transmission level. The spring constant and spring force for spring-washer isolator were selected to coincide with those of the rubber isolator. As shown in Fig. 8, the rubber isolator reduced the noise level by 5.5 dB (A) at 1.6 kHz and the spring-washer isolator reduced it by 3 dB (A) at 1.6 kHz. This noise reduction effect difference between these two isolators was caused by the damping characteristics. On the other hand, the laminated-steel-isolator increased the noise level by 5 dB(A). We haven't identified the reason for this noise level increase, but this isolator design might need to be optimized in terms of frequency characteristic and the fixing method. As a result, we chose the rubber material for common rail isolation material.

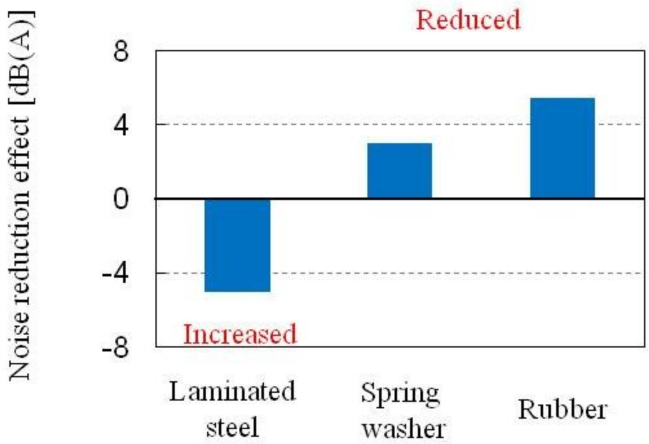



**Figure 8. Noise reduction effect of rail isolation material at 1.6 kHz**

SPL measurement results are shown in Fig. 9. This result compares the SPL of the spin-rig engine between the proposed system with and without rail isolation method. The testing condition was at idle running speed. Camshaft speed was 375/min (750/min in crankshaft speed), fuel pressure was 5 MPa, and injector pulse width was 0.8 ms. The SPL was measured in the one-third octave band and the average of four microphones SPL was calculated. As shown in Fig. 9, mid-frequency noise around 1~3 kHz was reduced by 5 dB (A). This mid-frequency noise level was reduced by the reduction of vibration transmission due to common-rail isolation. Moreover, high-frequency injector ticking noise above 5 kHz was reduced, and the maximum noise reduction level was estimated to be 3dB (A). Here, this dotted line was estimated from the results of comparing the system with/without the injector suspension method for a V8 spin-rig engine.

To clarify the relationship between the high-pressure pump pressurization event and noise radiation timing, we performed a short-time FFT. The results are shown in Fig. 10. The setup and condition for this testing were exactly the same as for the SPL measurement. The result for the proposed system without the common-rail isolation method shows strong impact noise between 1 and 3 kHz. In particular, the duration of this strong impact noise was long during the pump pressurization event. On the other hand, this strong noise impact was reduced dramatically by adopting the proposed rail isolation method. This strong noise impact in the frequency range between 1 and 3 kHz was reduced by the common-rail isolation method by attenuating the vibration transmission level from the high-pressure fuel system to the engine block.

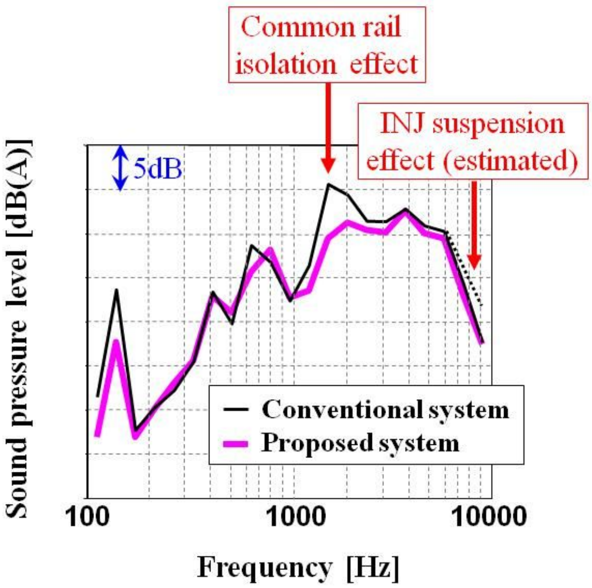



Figure 9. SPL of spin-rig engine with high-pressure fuel system

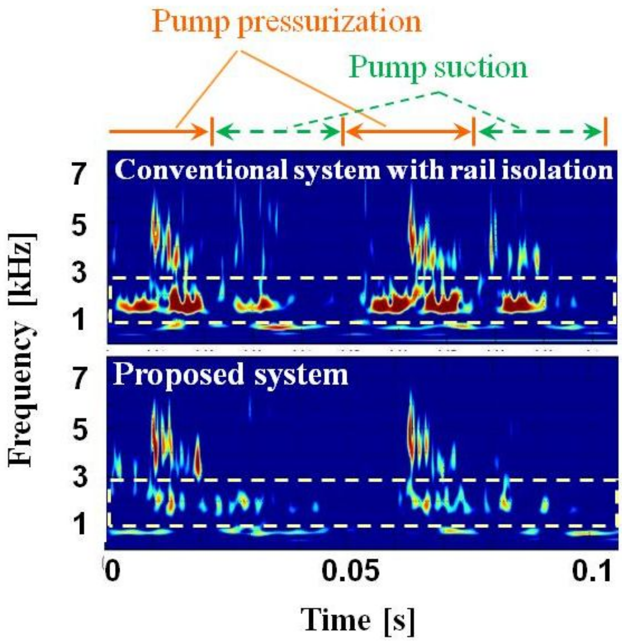



Figure 10. Results of short-time FFT analysis of sound pressure

## 5 Summary and Conclusions

The noise level of gasoline DI engine is high compared to that of the conventional gasoline engine. In an idle state, the driver or a passenger perceive just engine noise, and ticking noise from the high-pressure fuel system of gasoline DI engine is noticeable, which can reduce vehicle quality and customer satisfaction.

We developed a novel method for reducing noise level associated with the high-pressure fuel system in gasoline DI engines. The two main ideas in the method are to suspend the fuel injector from the common-rail and isolate the fuel rail from the cylinder head. Mid-frequency noise in the 1 to 3 kHz range can be reduced by 5dB by isolating the fuel rail from the cylinder head with a rubber-like damping material. High-frequency injector ticking noise above 5 kHz can be reduced by 3dB by suspending the injector from the fuel rail.

## 6 References

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