

Radio Frequency Diesel Particulate Filter Soot and Ash Level Sensors: Enabling Adaptive Controls for Heavy-Duty Diesel Applications

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ABSTRACT

Diesel Particulate Filters (DPF) are a key component in many on- and off-road aftertreatment systems to meet increasingly stringent particle emissions limits. Efficient thermal management and regeneration control is critical for reliable and cost-effective operation of the combined engine and aftertreatment system. Conventional DPF control systems predominantly rely on a combination of filter pressure drop measurements and predictive models to indirectly estimate the soot loading state of the filter. Over time, the build-up of incombustible ash, primarily derived from metal-containing lubricant additives, accumulates in the filter to levels far exceeding the DPF's soot storage limit. The combined effects of soot and ash build-up dynamically impact the filter's pressure drop response, service life, and fuel consumption, and must be accurately accounted for in order to optimize engine and aftertreatment system performance.

This work applied a radio frequency (RF) sensor to directly monitor diesel particulate filter soot and ash levels, thereby enabling direct feedback control of the filter based on its actual loading state. Results from fleet tests with Volvo/Mack trucks, over predominantly urban drive cycles, indicated the potential to decrease regeneration duration and associated fuel consumption by 50% to 75%, depending on operating conditions, and also to extend the time between active filter regenerations. Additional testing evaluated the performance of the sensor to distinguish soot from ash and define the DPF ash cleaning based on the actual measured ash load, as opposed to a prescribed filter maintenance interval. The results are useful to develop advanced control strategies to minimize the DPF-related fuel penalty, extend the service life of the filter, and identify anomalies indicative of filter failures or engine malfunctions.

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INTRODUCTION

Ceramic honeycomb-type diesel particulate filters (DPF) are now used on nearly all on-road and many off-road applications to reduce particulate matter (PM) emissions to mandated levels. The most prevalent filter materials include cordierite and silicon carbide, although others including aluminum titanate, are also seeing increased use. Regardless of the specific filter material, the wall flow design of the filter and porous walls, with a typical pore size from 10 μm to 20 μm , is extremely effective at trapping PM [1]. Particle trapping efficiency increases with increasing PM loading of the filter and may exceed 99% in many cases [2].

PM accumulation in the particulate filter restricts exhaust flow through the DPF and increases exhaust backpressure. In order to maintain exhaust backpressure levels below acceptable limits, and also to reduce the impact of the exhaust flow restriction on vehicle fuel consumption, the accumulated soot is removed from the filter through an oxidation process. This oxidation process, regeneration, may be accomplished through one of two paths. Active regeneration requires a commanded

increase in exhaust temperature, generally above 550 °C, to the point at which the accumulated soot oxidizes in the presence of excess oxygen in the diesel exhaust. Conventional active regeneration systems include exhaust hydrocarbon dosing upstream of a diesel oxidation catalyst (DOC), late in-cylinder post-injection, the use of dedicated burners in the exhaust, or electric heaters, in some applications. On the other hand, passive regeneration generally relies on the use of a catalytically-coated DPF, with or without a supplemental upstream DOC, to convert exhaust NO to NO₂ which promotes soot oxidation at lower temperatures, generally in the range of 250 °C to 300 °C [3].

The choice of regeneration strategy is closely linked to the engine and vehicle operating conditions and drive cycles. Critical parameters for efficient passive regeneration include NOx/PM ratio and the attainment of sufficiently high exhaust temperatures within an acceptable range over a required portion of the drive cycle. Catalyzed filter systems also require ultra-low sulfur diesel fuel (ULSD), typically below 15 ppm sulfur in the United States, to avoid sulfur poisoning of the

catalyst [4]. In contrast to passive regeneration, the degree of dependence on engine operating conditions for active regeneration varies. Active regeneration systems which rely on exhaust hydrocarbon injection or late in-cylinder post-injection for thermal oxidation over the DOC still require exhaust temperatures above the DOC light-off temperature for regeneration. Dedicated burners or electrically-heated systems, on the other hand, utilize a heat source mounted in the exhaust to directly heat the gas stream entering the DPF, and may operate nearly independent of the engine.

Regardless of the regeneration method, oxidation of the PM results in a small amount of residual ash, which accumulates in the filter over time. While the vast majority of the PM, generally around 99%, is composed of carbon, soluble organic material, and sulfates, which may be oxidized, the engine-out PM does contain a small fraction of incombustible material or ash. The ash is primarily composed of lubricant additives, including Zn-based anti-wear additives and Ca- and Mg-based detergents, however engine wear metals, exhaust system corrosion products (iron oxide), and fuel-derived elements may also contribute to ash in some cases [5, 6]. Over time the build-up of ash in the DPF requires filter removal for ash cleaning or replacement, as the ash reduces the filter's soot storage capacity and further restricts exhaust flow.

It is interesting to note, that ash levels in the DPF typically far exceed the soot levels in the filter, following extended DPF operation in the field. Assuming a typical maximum filter soot level (prior to regeneration) of 6 g/L, and filter ash levels ranging from 20 g/L to 40 g/L, the soot comprises only 23% to 13% of the material trapped in the DPF, with the vast majority being ash [7]. The absolute quantity of ash, which accumulates in the DPF, is a direct function of the engine's oil consumption and lubricant ash content, under normal conditions where the lubricant-derived ash is the largest contributor [8]. However, for engines operating on fuels with even single ppm levels of trace metals, or in ambient environments with high levels of incombustible dust (Si, Na, other metallic components), the non-lubricant ash contribution can be significant.

Ultimately, the accumulation of both soot, defined in this paper as the combustible portion of the PM, and ash, defined as the incombustible portion of the PM, negatively impact engine fuel consumption and filter service life. The fuel consumption penalty attributed to the DPF is a direct function of the increase in exhaust backpressure as soot and ash accumulate in the filter, and also a function of the regeneration penalty for actively regenerated filters. For on-road applications, the backpressure-related fuel penalty, attributed solely to soot accumulation, is estimated around 2%, while the active regeneration penalty is estimated to range from 2% to 5%, depending on the regeneration frequency [9]. More recent studies have also shown the accumulation of ash to contribute another 1% to 2% to the back-pressure related fuel penalty, in addition to the soot in aged DPFs [7].

Thermal management, regeneration control, and efficient filter maintenance (ash cleaning) of the DPF is, therefore, extremely important to minimize the system's overall fuel penalty and maximize component life. Currently, measurements of filter pressure drop, combined with predictive models, are used to indirectly estimate the loading state of the filter. The models range in complexity from simple time or mileage based regeneration triggers to more sophisticated estimates of engine-out soot emissions, passive soot oxidation on the filter, and ash accumulation, and are employed to improve the accuracy of the pressure-based estimates. Variability of up to 50% in the predicted DPF soot levels relative to actual measured filter soot levels, has been reported, for conventional pressure-and model based controls, depending on the engine operating conditions. Sources of variability include the well-known soot pressure-drop hysteresis, the impacts of varying exhaust flow rate and temperatures on the pressure measurements, and added contribution of ash accumulation to the pressure drop over time. As a result, many DPF control strategies employ a relatively conservative approach to avoid excessive soot build-up in the filter which can lead to thermal run-away (uncontrolled regeneration) and destroy the filter.

Recently, several studies have highlighted additional factors which can contribute to large errors in pressure-based estimates of DPF soot load. Under certain operating conditions, particularly in passively regenerated DPFs with high NO₂ levels generated near the filter walls, a phenomenon has been observed whereby the soot layer in portions of the channels may collapse, giving rise to a sudden increase in pressure drop. This jump in pressure drop results in an artificially high estimate of filter soot levels, in some cases two-to-three times higher than the actual filter soot load [10]. Additional regeneration studies, monitoring the change in filter pressure drop as a function of PM oxidation, have shown the measured pressure drop rapidly decreasing to near background levels with 50% of the soot mass still remaining in the filter [11]. The various processes affecting DPF pressure drop measurements further complicates the use of pressure sensors to meet on-board diagnostics requirements (OBD).

Ash distribution and the characteristics of the ash deposits have also been shown to have a large impact on the measured filter pressure drop. A recent comparison of the pressure drop levels for two filters, obtained from vehicles operating in the field with nominally the same ash mass (35 g/L - 36 g/L), showed their measured pressure drop values differing by a factor of two. Variations in ash distribution, including ash bridging of the channels and voids in the ash plugs were attributed to the observed differences in pressure drop [12]. Furthermore, studies of the initial ash build-up processes in (new) clean DPFs have shown the formation of a thin ash membrane along the channel walls also contributes to a decrease in filter pressure drop, relative to a clean DPF, at the same soot load, due to a decrease in soot depth filtration attributed to barrier formed by the ash membrane [13].

RF Sensing Fundamentals

The various processes affecting pressure-based estimates of the filter loading state have motivated the development of radio frequency (RF) - based sensors to directly measure soot and ash levels in the DPF. Figure 1 presents an overview of such a system showing the RF signal propagating through the ceramic filter and catalyst contained in the metallic housing.

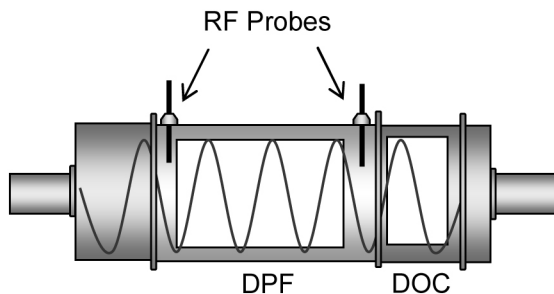


Figure 1. RF signal propagation throughout filter and catalyst housing.

As shown in Figure 1, one or two RF probes, essentially small rod antennas, are used to transmit and receive radio frequency signals through the DPF housing. The system is designed to operate below the cut-off frequency of the exhaust pipes, ensuring that the signal is fully-contained inside the metallic filter housing as the waves are too large to propagate down the exhaust. Furthermore, the signal may propagate through multiple filter or catalyst elements contained within the same housing, also shown in Figure 1. As the RF signal propagates through the filter media or catalyst substrate, provided the media or substrate is non-conducting, it provides a direct measurement of the soot or ash accumulated on the filter.

Fundamentally, the RF measurements respond to changes in the dielectric properties of the sampled volume; the DPF in this case. The accumulation of soot and ash on the DPF affect the dielectric properties of the filter, which has a profound effect on the RF signal. In particular, soot exhibits a very high dielectric loss tangent, meaning that the soot is a strong absorber of the RF signal. The build-up of soot in the filter would, thus, be expected to strongly attenuate the signal. Ash, on the other hand, exhibits a much smaller loss factor, but has a dielectric constant sufficiently different from the soot, filter, and media which it displaces, enabling the detection of ash in addition to soot. A comparison between the RF signal for a clean and loaded filter is shown in Figure 2.

The RF signal for the loaded filter clearly shows the attenuation and frequency shift in the signal relative to the clean case. The figure further shows five distinct peaks, which correspond to the first five resonant modes of the filter. Monitoring the signal at resonance provides increased sensitivity to measure soot and ash levels in the DPF (where the signal is strongest), and provides additional information related to the spatial distribution of the accumulated material. Fundamentally, each resonant mode corresponds to a specific electric field distribution within the housing, and modeling studies coupled with experiments were described in a previous publication by the authors [14].

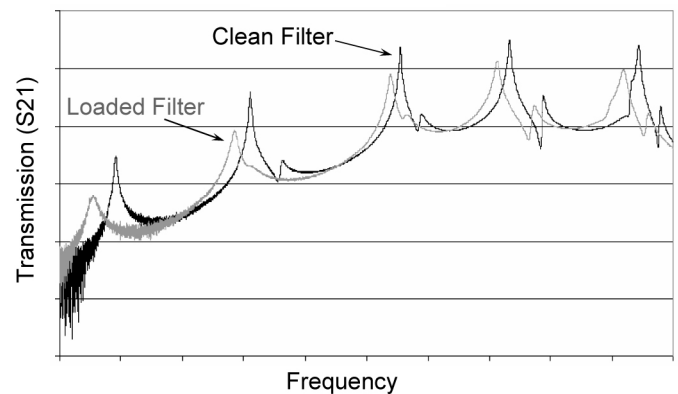


Figure 2. Resonant characteristics of a clean and loaded filter over a broad frequency range covering five resonant modes.

Additional details related to RF sensing fundamentals applied to DPFs are available in [15, 16]. The RF-based sensing system described in this paper differs from previous approaches in that the system monitors the change in the signal parameters at resonance, where the signal is most sensitive, as opposed to the absolute power loss at a single frequency or narrow frequency band [17].

Sensor Hardware

The Filter Sensing Technologies (FST) sensor hardware is shown in Figure 3 and consists of two components. The first is the RF probe shown in Figure 3(a). The probes are essentially small stainless steel rod antennas, of similar size and formfactor to a conventional exhaust temperature sensor, also shown in Figure 3(a) for comparison. The second component consists of the RF control unit, shown in Figure 3(b).

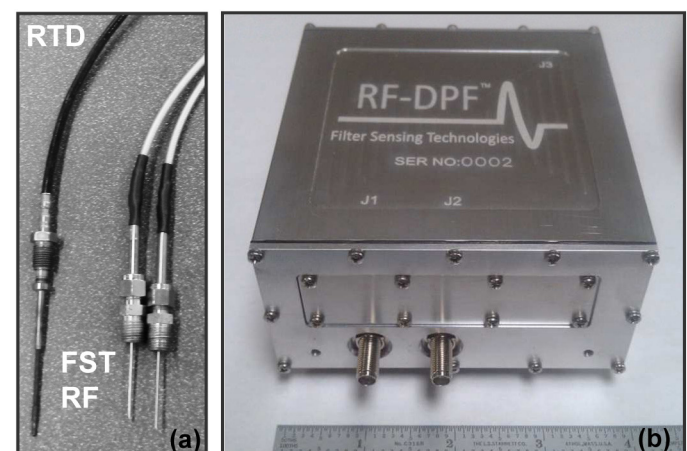


Figure 3. RF sensor hardware showing comparison of RF probes with conventional exhaust RTD (a) and RF control unit (b).

The RF control unit, shown in Figure 3(b), is capable of both transmission (two-port) and reflection (single-port) vector measurements, which includes measurements of amplitude and phase over a broad frequency range, spanning 0.4 GHz to 2.4 GHz. The systems, thus, allows for considerable flexibility to conduct transmission measurements as well as reflection measurements described in this paper, as well as reflection measurements.