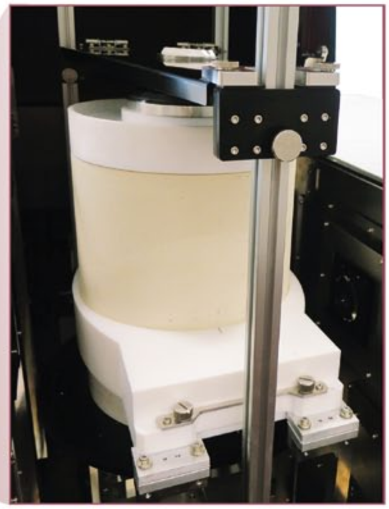


A NEW TERAHERTZ ANALYTICAL TOOL FOR EXHAUST AFTERTREATMENT SYSTEMS

Effective regeneration of the particulate filter and removal of ash have a favourable influence on the performance of a diesel engine and help to reduce fuel consumption. The innovative TAS7000 Imaging Analysis System from Advantest Europe GmbH is a new, non-destructive analysis system that uses terahertz (THz) wave technology to examine the exhaust system components and to assess the system's performance.

AUTHORS

JÜRGEN ROTT,
is Technical Support Engineer, TAS Project, at Advantest Europe GmbH in Munich (Germany).

JUDY FEUERBACH,
is Consultant TAS at Advantest Europe GmbH in Munich (Germany).

YOSHI MITANI,
is Product Manager TAS, Products & Services at Advantest Europe GmbH in Munich (Germany).

BACKGROUND

In 2011, Advantest completed a quantitative study to characterise and map the density distribution of particulate matter (PM) and ash, as well as determine the ash cleaning effectiveness, using a single cordierite c-DPF (diesel particulate filter). The study results demonstrate terahertz wave's unique capabilities to provide data that can be a critical tool in developing efficient after-treatment systems in compliance with new diesel exhaust emissions requirements.

TERAHERTZ WAVE TECHNOLOGY

In the electromagnetic spectrum, terahertz waves have frequencies between radio and light waves, resulting in waves that have both the transmissivity of radio waves and the directivity of light waves, ❶. These low energy electromagnetic waves possess remarkable properties including absorption spectra that enable them to penetrate visually opaque materials. Because of its low energy, THz wave does not ionise or damage an electron from an atom or molecule and is sensitive to light atoms such as carbon (soot). Therefore, it is a non-destructive technique. In contrast, X-ray, is ionising, breaks molecular bonds, and has little sensitivity for light atoms (carbon/soot).

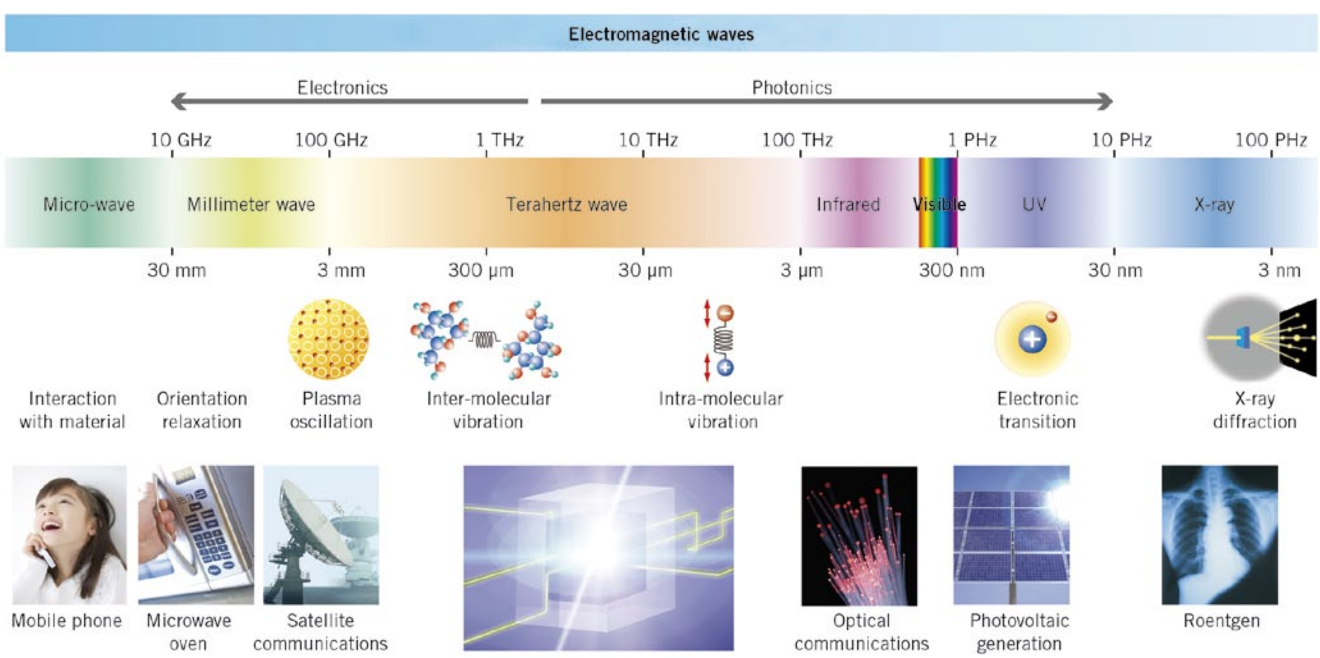
THz wave's good penetrability of ceramic substrates (Cordierite, Aluminum-Titanate, Mullite) and catalytic coatings can be used to analyse the interior of a DPF, a diesel oxidation catalyst (DOC) and other emission system components (SCR, LNT, etc.). Computed tomography (CT) technology uses the THz wave spectral information to provide a quantitative 3D distribution mapping visualisation of substrate homogeneity, catalytic coating coverage, soot and ash accumulation and post cleaning efficacy. The data generated from this measurement technique can be applied to make better modeling possible for improvements in:

- DPF and exhaust gas after-treatment system design
- uniformity of exhaust gas flow
- engine control optimisation
- defect reduction.

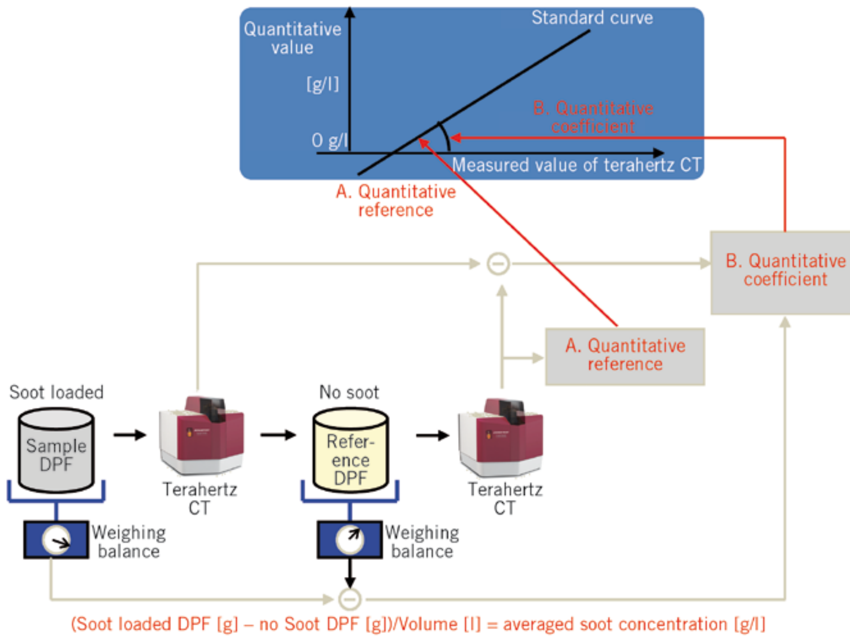
Until recently, THz techniques had not been developed for commercial use. Advantest has applied its proprietary terahertz wave technology to non-destructive analysis and characterisation of after-treatment systems for exhaust emissions.

THE STUDY

Advantest performed TAS7000 non-destructive THz CT for two and three dimensional (2D & 3D) distribution mapping using the spectroscopic pro-



❶ Terahertz wave in the electromagnetic spectrum



❷ Quantitative analysis procedure for THz CT

perties of terahertz light waves at three different stages of the same DPF:

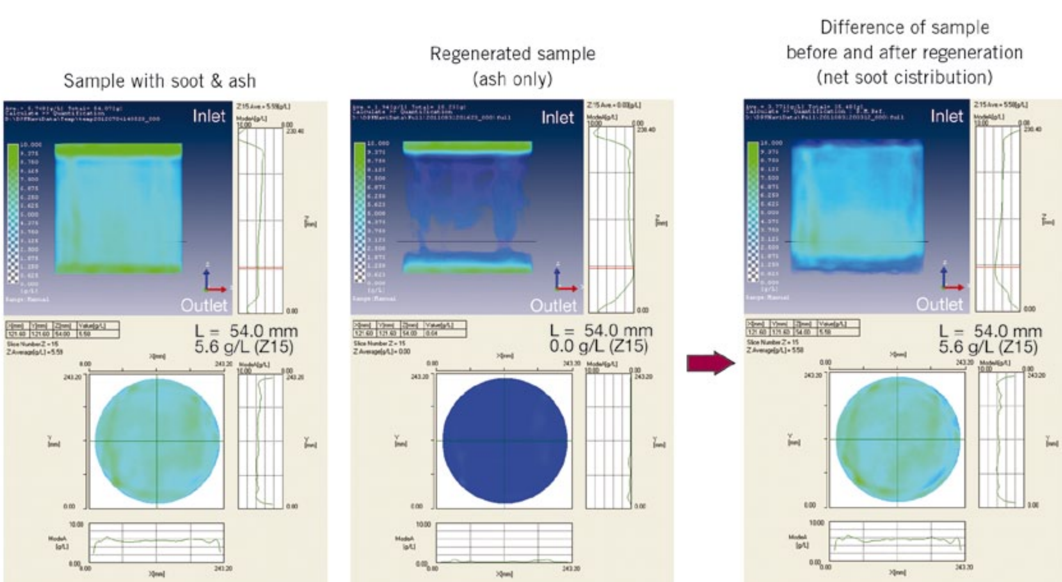
- : post soot loading
- : post regeneration
- : post ash cleaning.

Liebherr Machines Bulle (Switzerland) provided a 9” D x 9” L Cordierite filter with washcoat (c-DPF) with 200 CPSI at 12/10.000 inch mil. Before each analysis, the substrate was placed in a drying oven at 150 °C for three hours to remove any moisture that may influence weight measurement and terahertz wave transmission through the sample. The sample was loaded with soot and ash and then analysed by THz CT to characterise the soot load and distribution. This same filter was again measured after regeneration for ash characterisation and then measured a third time after cleaning to evaluate the cleaning process effectiveness.

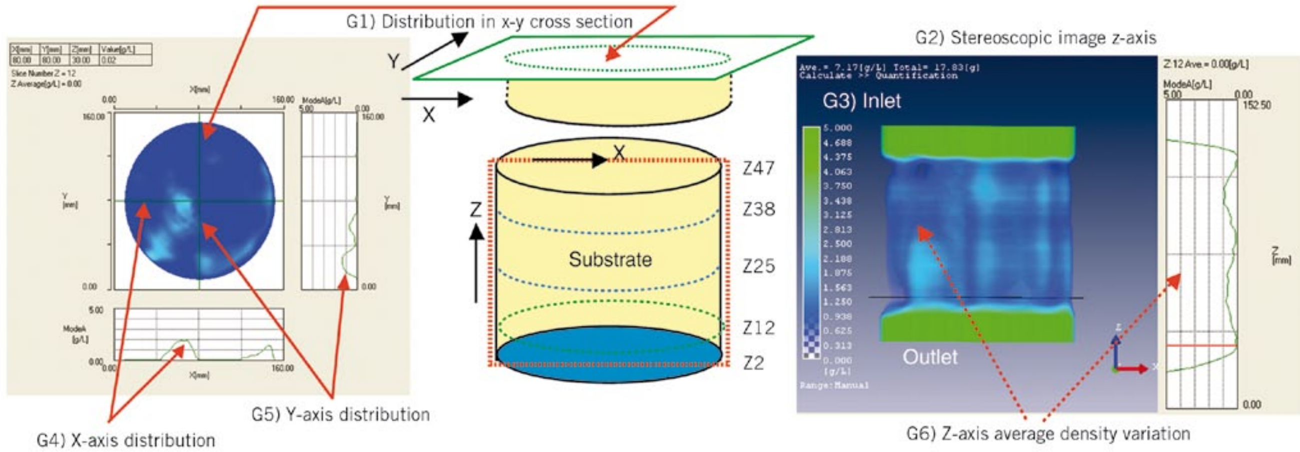
QUANTITATIVE ANALYSIS MEASUREMENT

The quantity of the target substance distributed within the sample can be measured in 3D via the construction of a calibration curve for the 3D tomographic qualities measured. ❷ shows the reference values and the method of determining fixed quantity coefficients.

THz wave CT analyses the reference sample containing no soot. The measured values are taken as the calibration curve reference values such that the substrate density prior to soot loading becomes 0 g/l or the baseline. Then, for the substrate loaded with soot, the average value of the difference between the THz transmission parameter and the



❸ Base material reference method



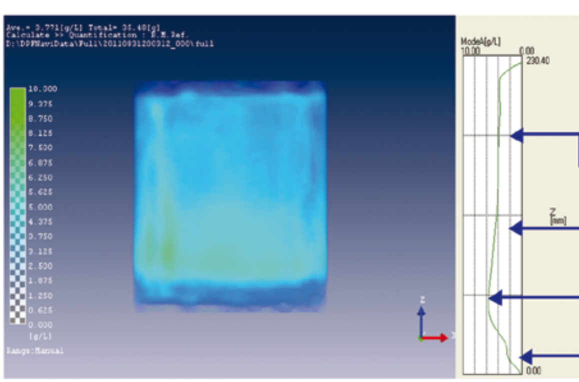
❹ Perspective of the analysis results

reference value is calculated. A gradient (coefficient) of the calibration curve is determined as the ratio of the average and the expected value. The calibration curve is then applied to all 3D tomographic data. By applying the calibration curve to the 3D tomographic data, the TAS7000 provides a 3D image and quantitative distribution of the target material (in this case, soot and ash) throughout the filter.

Optimally, the same filter would also be measured as a bare filter for substrate irregularities and after catalyst coating for coating coverage variations to ensure a comprehensive, quantitative life stage DPF performance characterisation from bare filter to post regeneration cleaning. In this instance, the scope of the study was limited to the three stages listed above and the regenerated filter was used as a baseline to calculate the average density of soot, ❸. Using this method, the substrate and coating irregularities plus ash could be eliminated by subtracting the regenerated, ash only sample data, ③ (middle) from the soot and ash loaded Sample, ③ (left) so that only the soot data could be visualised, ③ (right).

DATA PROVIDED

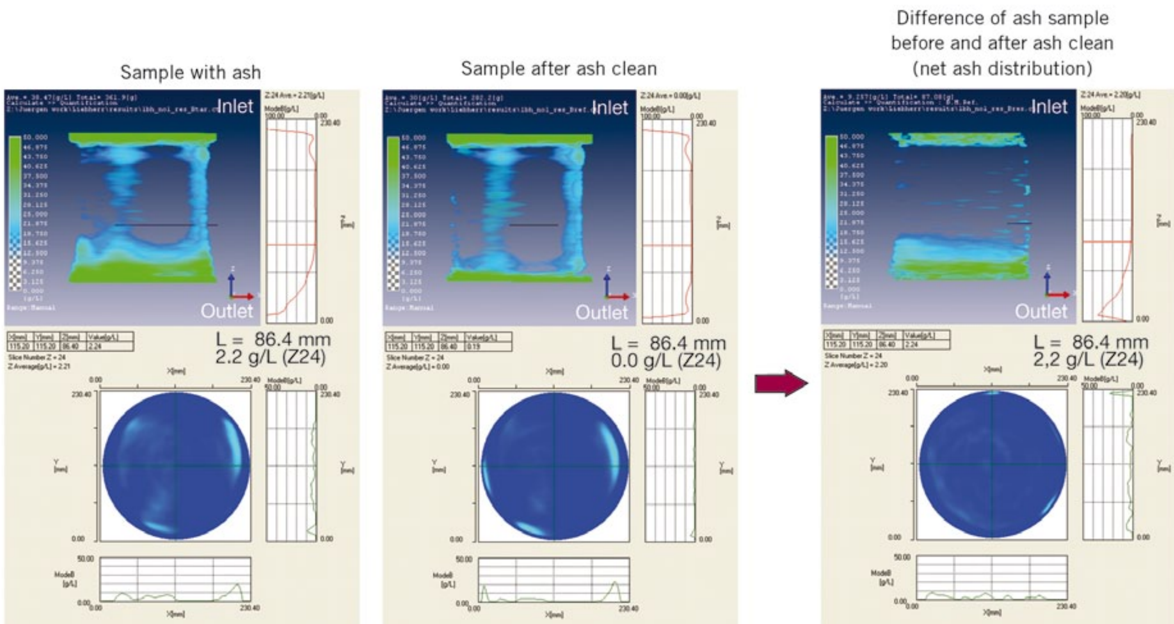
For each cross-section slice, the TAS7000 can display five different results for an overview of the target material (substrate, catalyst, soot, ash, etc.) distribution and density. The five results are comprised of a 2D cross sectional image, a stereoscopic image and three spectral images. The 2D image is the target material variation across the X-Y axis, G1 in ❹. The 3D image is viewed from the horizontal direction along the plane across the vertical axis. It displays the target material variation through the length of the Z axis slice, G2 in ④. TAS7000 also displays the total average density of the selected slice in grams per liter, G3 in ④. Density is defined as the target material weight per liter of substrate volume. Two of the three spectra depict the density variation across the X axis, G4 in ④, and across the Y axis, G5 in ④, of the cross section. The third spectrum shows the



Average density variation in the z direction

		TAS 7000	Gravimetric method
Total DPF average		4.0 g/l	4.0 g/l
2D cross section average	L 169.2 mm (Z47)	3.8 g/l	—
	L 86.4 mm (Z24)	4.9 g/l	—
	L 50.4 mm (Z14)	5.6 g/l	—
	L 14.4 mm (Z4)	2.4 g/l	—

❺ Net soot distribution



❻ Stereoscopic and 2D images of cross section slice Z24

average density variation along the Z axis, G6 in ④. The combination of these images gives a clear characterisation of the target material density and variation within the cross section slice and the entire substrate.

THE FINDINGS

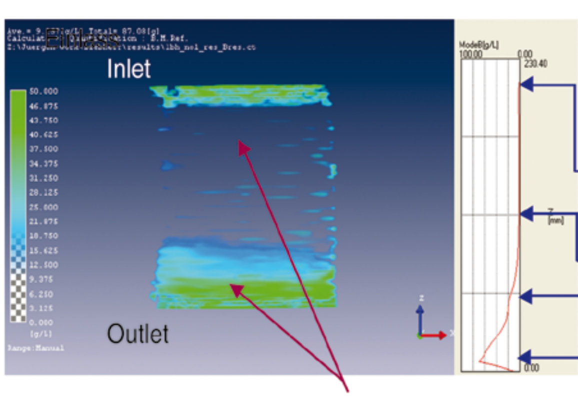
For the soot loaded sample analysis, the average particulate material was calculated at 4 g/l. On the Z axis (height), the soot was highly concentrated towards the outlet side of the filter between cross section slice Z10 and Z20 as can be seen in ❺ in the 3D image and the spectrum to its right.

The cross sectional slice Z14 represents one of the highest soot density slices with an average soot density of 5.6 g/l. On the X-Y cross sections, the soot density shows deeper and lighter density areas indicating variations in the soot loading. The higher particulate material density closer to the outlet is attributed to pressure drop and exhaust flow changes from inlet to outlet.

For the ash only sample, the average ash load was 9.8 g/l. Similar to ③, the substrate irregularity may be removed by subtracting the ash cleaned filter data so that only the ash data could be visualised, ❻.

In the Z Axis (height), the ash density is consistently light from the inlet side of the filter to the lower centre. It becomes denser toward the outlet side with the highest density close to the outlet. The density distribution on the X-Z cross sections shows high density around the outlet and almost no accumulation in the upper half of the filter, ❼.

After analysis, the ash only sample was cleaned of ash and again analysed. The efficacy of the ash cleaning process can also be clearly seen in ⑥ (middle). The highest density ash accumulation close to the outlet has been significantly reduced. The Z axis spectral curve post cleaning is significantly less than that for the post regeneration (ash loaded) Z axis spectrum on the left. The cross sectional



Average density variation in the z direction

		TAS 7000	Gravimetric method
Total DPF average		9.8 g/l	9.8 g/l
2D cross section average	L 205.2 mm (Z57)	0.6 g/l	—
	L 111.6 mm (Z31)	0.4 g/l	—
	L 54.0 mm (Z15)	15.7 g/l	—
	L 14.4 mm (Z4)	57.7 g/l	—

The density distribution on x-z cross section shows high density in around the outlet and almost no ash accumulation at upper half (inlet).

❼ Net ash distribution

slice Z24 confirms this finding at 2.2 g/l on the ash loaded filter but 0.0 g/l on the cleaned filter. Variations across the X-Y axis spectrum show a reduction in ash on the cross sectional view. By using the base reference method, the substrate and wash coat variation images could be suppressed to display only the ash removed with cleaning.

CONCLUSION

In this study, the TAS7000 Imaging System used THz wave technology with computed tomography to measure a single sample filter at three stages and clearly characterised:

- variations in soot loading from inlet to outlet and across the X-Y axis
- effective soot regeneration with post regeneration ash accumulation at the outlet
- significantly reduced ash post cleaning, indicating an effective cleaning process.

Although not included in this study, THz CT can characterise DPF performance by the optimal measurement sequence of a single bare filter throughout the coating, soot loading, regeneration and ash cleaning processes. The resulting quantitative and qualitative data can be used to help identify the influences or damage contributed from substrate variations, coating anomalies, inconsistent soot loading, ineffective regeneration and incomplete ash-cleaning.

Through multiple analyses of the same sample in this study, it has been shown that non-destructive THz wave CT measurement is repeatable and reproducible. The non-destructive properties of THz wave also make it the only tool that can conduct such a study.

THz wave technology can be applied to measure and characterise individual system components as well as the entire exhaust aftertreatment system performance. THz wave measurement can be used as a tool in designing more efficient systems by:

- incorporating the extensive data into exhaust gas flow design models
- conducting active regeneration studies to optimise engine control
- characterising poisoning material distribution and high temperature regeneration effects on them
- analysing defects for optimal maintenance schedule development.

THz wave technology has proven to be a viable new measurement technique for current and future performance characterisation, troubleshooting and exhaust system design in compliance with regulatory exhaust emissions requirements.

THANKS

A DPF with soot and ash was provided by Liebherr Machines Bulle Switzerland (Roland Wiltz and Dr Regis Vonarb).