JSAE 20119512 / SAE 2011-32-xxxx

Accelerated Durability Test for Metallic Substrates Tailored for Motorcycle Application

Lorenzo Pace, Francois Jayat, Roman Konieczny
Emitec G.m.b.H.

Martin Forster, Rudolf Prem, Richard Humer
KTM Sportmotorcycles AG

Copyright © 2011 SAE Japan and Copyright © 2011 SAE International

ABSTRACT

Future emission legislation for 2 and 3 wheelers in EU, USA and many other Countries will introduce durability of pollution control devices following the example of the People Republic of China. Along with a durable coating technology, the mechanical durability of the substrate must be ensured to guarantee the requested conversion efficiency for the entire life of the motorcycle.

A traditional approach consisting in engine bench and vehicle testing is no more competitive considering the very short time to market needed in the motorcycle market and the relevant cost related to this kind of tests. For this reason a new time and cost efficient accelerated component durability test was developed, which can account for the combined effects of critical load at a metallic catalytic converter.

This paper shows the methodology used to determine the critical stressors and their levels in real operating conditions by measuring and analyzing a broad range of vehicle test information. The information was used to develop a temperature profile and a high vibration load, which were implemented in a superimposed hot vibration / thermal cycling component bench test.

This highly accelerated test provides a time and cost efficient reproduction of field failure modes and allows the project team to choose a tailored and robust design for metallic catalytic converters without any risk regarding the durability and, on the other hand, to avoid any over engineering.

INTRODUCTION

The purpose of this accelerated life test is to confirm the mechanical robustness of the metallic catalytic converter ensuring it provides complete conversion of emissions of the engine exhaust to meet legislated emissions standards throughout the useful life of the vehicle and under a wide range of real-world operating conditions.

The new test is an accelerated component bench test, specifically designed and developed for ensuring the "mechanical" robustness of the metallic catalyst matrix, the brazing system, and its mantle assembly within the complete exhaust system assembly for the useful life of the vehicle. Figure 1 depicts a typical metallic catalytic converter assembly.

Figure 1: Typical metallic converter

This accelerated life test does not include degradation of the washcoat catalytic function necessary to assess feedgas to tailpipe emissions reduction efficiency. This efficiency measure is established in certification protocols, and calibration sign-off for tailpipe emissions through the in-use assessment procedures.

The main focus of this test series is the development of a new combined hot vibration / thermal cycling test, which creates severe operating conditions and simulates a highly accelerated mechanical ageing of the metallic catalytic converter minimizing the vehicle testing.

In present work, for sake of clarity, the mechanical load analysis will be performed only for one motorcycle type, many other measurements have been carried out in the past in order to create a data base of boundary condition.

TEST BOUNDARIES DEVELOPMENT

BOUNDARY DIAGRAM

The accelerated life test applies only to the metallic catalytic converter assembly (sub-system components), which is classified as an aftertreatment control device within the exhaust system. Figure 2 depicts the generic metallic sub-system boundary diagram illustrating the relationship between the metallic catalytic converter and interfacing sub-systems and components of the exhaust system.

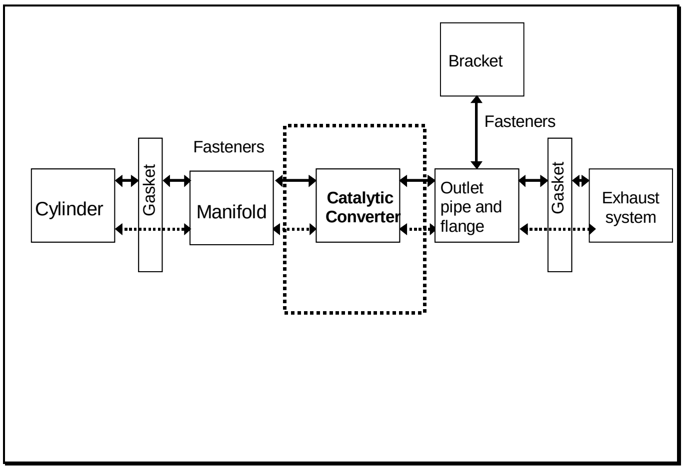

Figure 2: Generic catalytic converter system boundary diagram

FAILURE MODES, ERROR STATES

The basic mechanical function of the metallic catalytic converter is to retain the catalytic coated metal foil matrix (substrate) and to direct unrestricted flow of the exhaust gas from the exhaust manifold and/or down pipe through the catalytic coated substrate matrix to the vehicles exhaust system for the useful life of the vehicle.

Additionally, the chemical function of metallic catalytic converter is to convert HC / CO / NOX in the engine exhaust to primarily water vapor, carbon dioxide and nitrogen while conveying the exhaust gases to the muffler and pipe system. This chemical function is not covered in this life test.

The development of the functional relationship (Y=F (X) diagram) was used to identify and characterize two high level loss functions (error states) from a sub-system level, leading to noncompliance of regulatory requirements or customer dissatisfaction.

These error states at the mechanical life test level are:

YA: Loss of matrix integrity: mechanical change in matrix foil structure causing higher flow restriction or foil separation leading to untreated exhaust gas flow (pass by).

YB: Loss of matrix/mantle retention: mechanical loss of matrix-mantle interface joint causing partial or complete matrix detachment.

CRITICAL STRESSORS

To detect the critical stressors that cause the error states, a Pareto Analysis of the Design Failure Mode and Effects Analysis (DFMEA) of metallic catalytic converters was conducted and is shown in Figure 3. In this chart, the product of severity and occurrence is shown for the most probable failure modes. The level of occurrence for all failure modes was determined from Emitec design development and vehicle test data [**1**], and the severity of each failure mode was defined following established DFMEA guidelines [**2**].

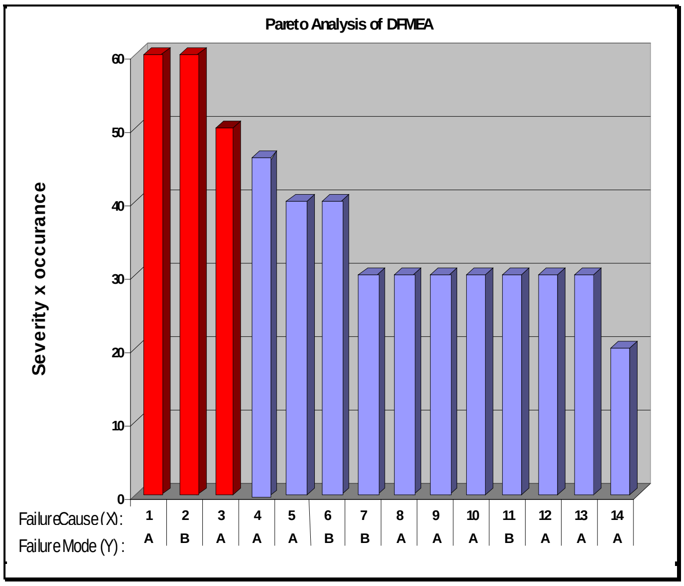

Figure 3: Metallic converter DFMEA failure mode/cause chart

The DFMEA failure mode/cause chart in Figure 4 shows, that the most severe and critical environmental stressors (noise, X1...X3) that can cause the mechanical function losses (YA, YB) of metallic catalytic converters are prioritized in the following order:

X(1) Temperature/Temperature change rates (transients) too high: This can lead to exceeding the mantle/matrix attachment capability to maintain dimensional and physical properties when exposed to severe thermal stresses.

X(2) Mechanical loads / frequency too high: High g-forces can exceed the design capability of the matrix and matrix/mantle attachment to hold the substrate in place. These g-loads provide the energy necessary for forcing the matrix out of the assembly when applied at high magnitude. The combination of high g-loads at the high frequency can even increase this effect.

X(3) Poor uniformity index for exhaust gas flow (mass and distribution): Impinging forces acting on the portion of the substrate with high localized flow concentration can lead to possible foil damage. High localized flow concentration at the matrix/mantle interface can result in possible failure of matrix/mantle retention.

REAL WORLD USAGE PROFILE

The new accelerated bench test was developed using vehicle test information and following standard reliability methods. First, the typical real world environment of a metallic catalytic converter was surveyed and the critical stressors were characterized as shown in Figure 4.

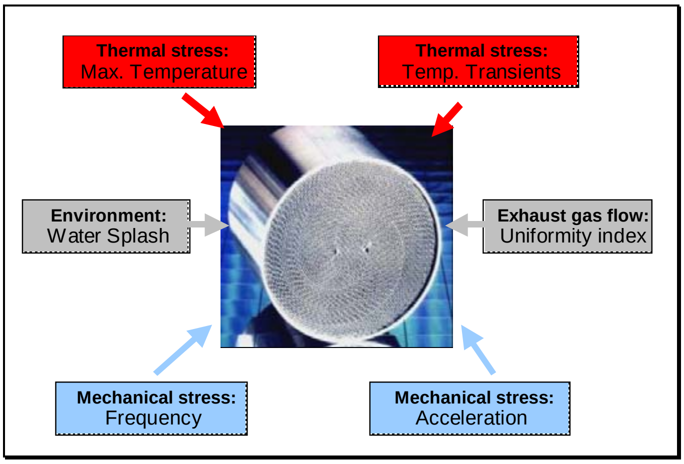

Figure 4: Real world environment of a catalytic converter

Future tighter emission legislations will increase the loads on the converter taking in consideration that the position of the converter itself will probably change from “in muffler” (major of EU2 applications and some EU3) to mid position. That will have particular effect on thermal and mechanical stresses but also on the uniformity index (due to the space constraint it will be more and more difficult to have high value of U.I.) and water splash (that was not considered in “in muffler” applications).

TEST SERIES DEFINITION

The level of the critical environmental stressors temperature and vibration was determined from measurements during Emitec vehicle characterization tests (Figure 5). These tests represent severe thermal and mechanical stresses on the brazing system and foil structure of metallic catalytic converters such as high temperature, rapid temperature transients and high vibration loads and are described further in section VEHICLE CHARACTERIZATION / DATA ANALYSIS.

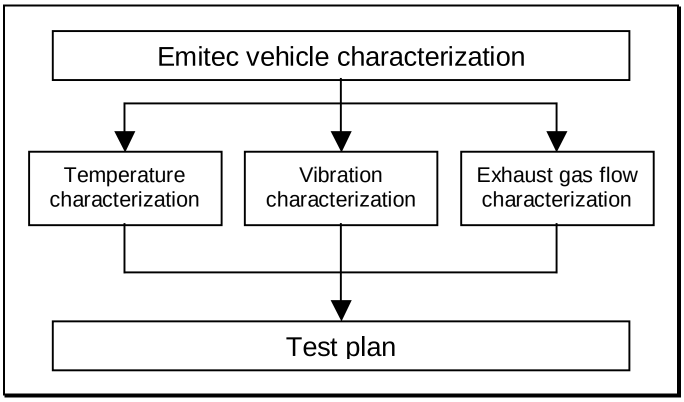

Figure 5: Test series definition process

The environmental thermal and mechanical stresses are then accelerated in a test laboratory through a combination of equipment (gas burner, shaker table, test fixture) and instrumentation (data acquisition system, analysis software). This is described in a test plan as shown in Figure 6.

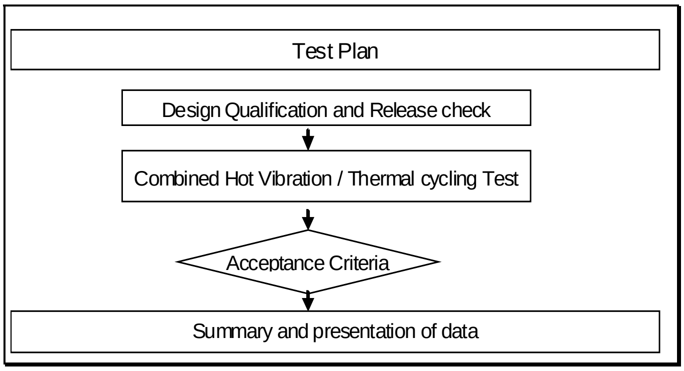

Figure 6: Test Series plan

VEHICLE CHARACTERIZATION AND DATA ANALYSIS

TESTED MOTORCYCLE

A state of the art modern superbike has been chosen to perform the vibration and temperature measurements. The 2-cylinder, 4-stroke, V 75°, 1195cc engine is equipped with EFI end λ-Sensor and deliver 129 kW at 10500 rpm with a torque of 129 Nm at 8000 rpm. The KTM RC8R (Figure 7) has a gross weight of 184 kg.

Figure 7: KTM RC8R: Motorcycle used for measurement

The exhaust muffler is located under the engine compartment; each cylinder blows in a metallic catalytical converter with 70mm diameter and 74.5mm length with 400cpsi and PE foils technology.

TEMPERATURE LOADS

To define the temperature boundaries for the accelerated bench test, temperature data was measured during a vehicle operation that consists of a steady phase with high temperature conditions followed by a number of Wide Open Throttle (WOT) accelerations. Each acceleration phase is followed by a downshift sequence for vehicle deceleration. This vehicle test is used by Emitec to characterize the maximum thermal loads on the catalytic converter during severe operating conditions [7, 8]. The measured temperature data are shown in Figure 8.

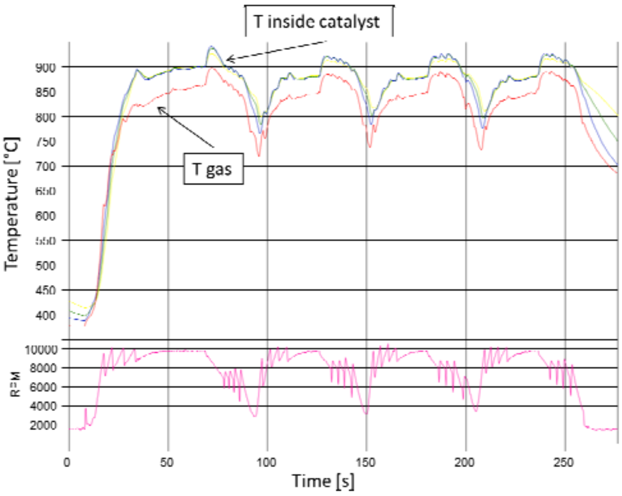

Figure 8: In-Vehicle Temperature data

T1 is the gas temperature, T2 is the temperature 2 mm inside the matrix from gas inlet side, T7 18 mm inside the matrix and T8 38 mm inside the matrix.

	Measure	Bench test
Max. temp. T1 [deg. C]	930	930
Min. temp. T1 [deg. C]	400	300
Max. positive temperature transient T1 [K/min]	2200	6000
Max. negative temperature transient T1 [K/min]	-750	-2500

Table 1: Boundaries of temperature and temperature transients

From these data, the maximum temperatures and maximum temperature change rates (positive and negative transients) have been determined. These data were used to define the boundaries of the temperature profile that is applied during the new accelerated bench test (see section BENCH TEST STRATEGY). The temperature transients are much higher than the measured values in order use higher loading in the bench test.

Table 1 shows the boundaries of temperatures and temperature transients of the new bench test.

VIBRATION LOAD

For reproducible analysis of vibration loads and frequency distribution, a number of tests has been carried out through an engine sweep test under WOT conditions (Figure 9). In this test, the vehicle is accelerated in fifth gear from minimum drivable engine speed to maximum engine speed with full open throttle. This operation represents the highest mechanical load to an engine and its attached components over the full engine speed range. It represents the maximum vibration load (acceleration and frequency) for the metallic catalytic converter. The vibration load data from this characterization test, which consists of low and high frequency data was then used to develop a vibration load profile that can be applied to the vibration shaker table during the bench test as described under section VIBRATION LOAD PROFILE.

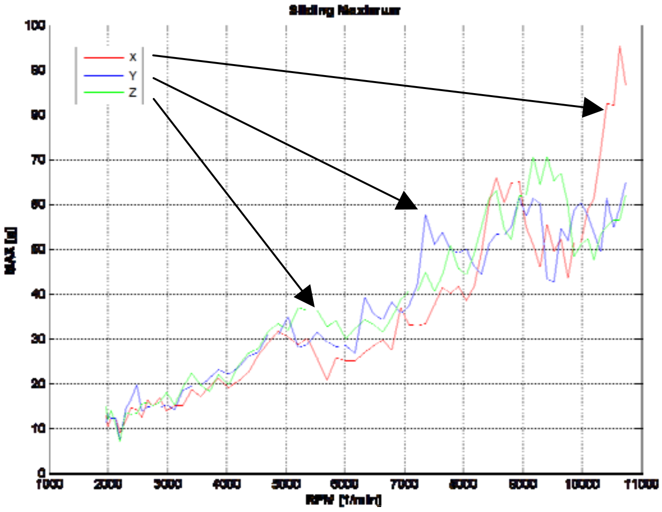

Figure 9: In-Vehicle vibration load

X direction is parallel to exhaust flow direction, y direction perpendicular to flow direction and parallel to street plane and finally z direction is perpendicular to flow direction and street plan.

Along with vibration load another important parameter is the presence of any resonance. Figure 10 shows the power spectra density of the tested catalyst. The power spectral density (PSD) describes how the power of a signal or time series is distributed with frequency. The power in the Z direction is high at very low frequencies while in X and Y direction is high around 2000 Hz.

It is important to investigate where the matrix – mantle resonances take place.

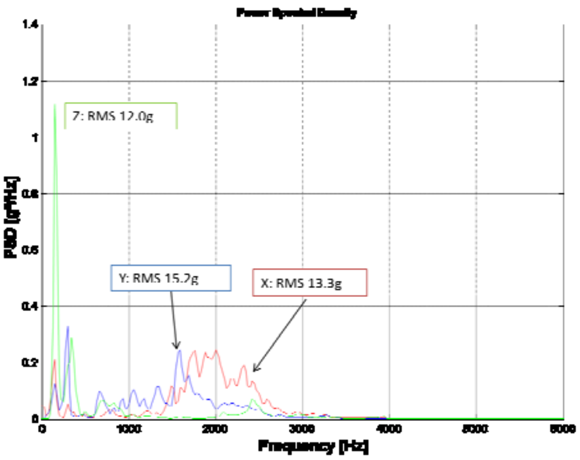

Figure 10: Power Spectral Density of the tested substrate

The matrix - mantle resonance of the substrate alone can be measured using the Polytec PSV-400-H4 Scanning Vibrometer. The substrate is mounted on an insulating table (Newport RS2000) and excited by a shaker. The matrix and mantle response are measured using the laser vibrometer (Figure 11). The first peak (~1700 Hz) is a general resonance of the measurement system.

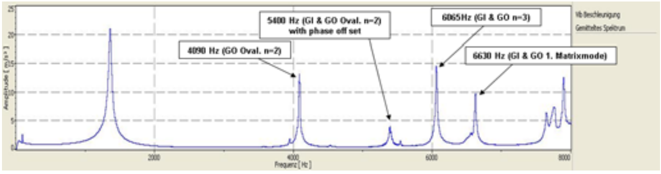

Figure 11: Resonances the tested substrate

Comparison test, carried out in the past, shows that the frequency spectra of the uncoated substrate at room temperature is 10 – 20% shifted towards higher frequency than the same substrate but coated, mounted in real vehicle and measured during engine running.

In this case, the matrix mantle resonance (6630 Hz) is well above the frequency range that can excite the substrate during real life operation, compare Figure 10 with Figure 11.

EXHAUST GAS PEAK FLOW AND DISTRIBUTION

The DFMEA analysis identified exhaust flow mal-distribution (Bias Flow) as a significant causal factor when combined with temperature and mechanical loads. Bias flow could result in high backpressure and high thermal gradients resulting in high thermal and mechanical stresses to the brazing system / foil structure.

Optimizing a uniform flow distribution (Uniformity Index, Gamma close to 1.0) and centered peak velocity location (Velocity Index close to 0) ensures robustness against bias flow. To eliminate this noise factor, most vehicle manufacturers have developed an exhaust specification for flow distribution that all catalytic converters must meet for engineering sign-off.

For the new bench test, a high exhaust gas mass flow was chosen, which represents the upper range of all surveyed vehicle applications at WOT operation. In the bench test, this high mass flow is combined with an uneven flow distribution to introduce accelerated flow conditions.

BENCH TEST STRATEGY

Based on the data evaluated from the vehicle characterization, the most significant load cycles were localized. The maximum and minimum temperature levels were determined and temperature transients were calculated. The transients describe the velocity of temperature change in positive and negative direction in the matrix in [degree K / minute].

The Ordered Overall Range Method [3] describes that only the most severe temperature cycles lead to cumulative failure. From a temperature profile measured in a vehicle, the highest and lowest temperature peaks of a sequence were defined. Small peaks between the selected events were discarded [5].

The Method of High Usage Rate or Time Compression Method [3] was used to reduce off-time during the temperature cycle and therefore stressing the tested parts at a greater fraction of the time. Instead of a stochastic occurrence of high load phases in normal operation, the test part is tested with much more frequent high-load events.

These methods lead to a significant test time reduction of the new accelerated life test. Figure 12 shows an example for a temperature sub-cycle during the accelerated bench test. This temperature cycle was derived from the vehicle temperature characterization by eliminating minor temperature cycles caused by gearshift events (Ordered Overall Range Method) and shortening the non-damaging phase of steady high temperature (Time Compression Method).

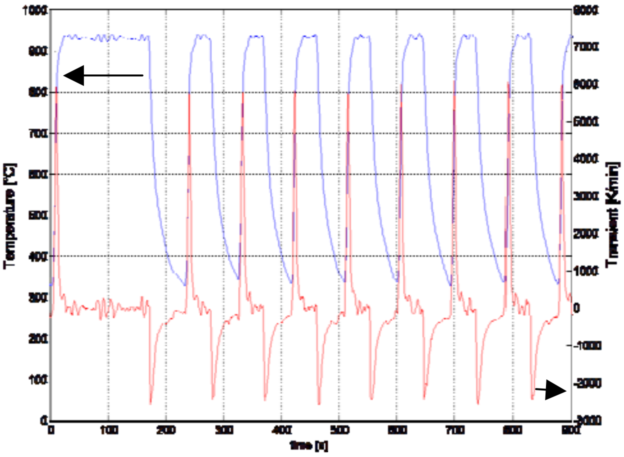

Figure 12: Example of temperature sub-cycle during the bench test

The bench test temperature cycle focuses only on a time-compressed occurrence of maximum and minimum temperatures and severe positive and negative temperature transients.

VIBRATION LOAD PROFILE

To simulate worst-case vibration in the accelerated life test, the same time compression test strategy was chosen. The acquired data from the vehicle tests have been analyzed, the vibration level and frequency were evaluated, and all events were then classified in order to identify the most severe vibration condition.

Figure 13 shows an example of measured RMS (Root Mean Square) acceleration level of all three converter main axis in the tested motorcycle. The maximum acceleration level for all directions was determined at an engine speed between 8300 and 11500 rpm. A comparison with Figure 9 shows a crest factor (ratio between max value and RMS value) of about 4.

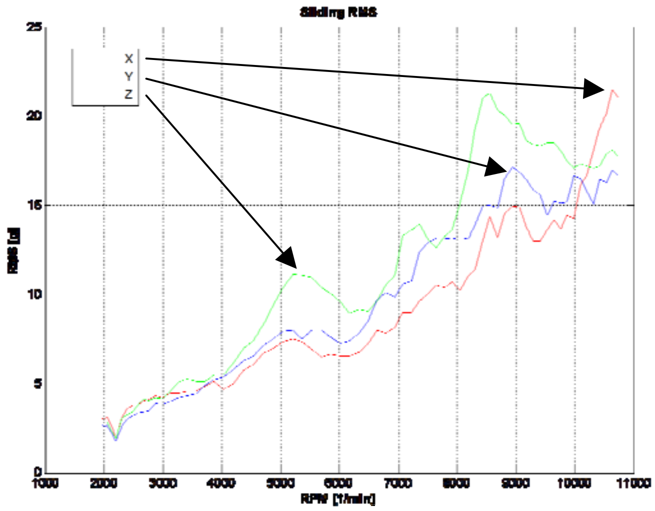

Figure 13: RMS acceleration while an engine sweep

By calculating the PSD of a vibration signal, the data are transformed from a time-based domain into a frequency-based domain. The PSD curve is an envelope curve, and the area under this envelope represents the square of the average vibration level (RMS).

To introduce a vibration load in the bench test that is representative for most vehicle applications and to avoid resorting to expensive vehicle testing for every new application, it was necessary to define a generic PSD envelope curve, which has a greater area under the envelope and therefore a greater average vibration load (RMS) than the vehicle PSD.

Assuming that higher accelerations occur at lower frequency and lower acceleration occur at a higher frequency, the generic bench test PSD curve was developed as shown in Figure 14. This PSD envelope curve covers the complete frequency range as measured in the vehicle characterization test.

Because it is a generic envelope curve, it cannot account for every single acceleration peak for each vehicle application; however, its average vibration load level (RMS) was defined to being representative for motorcycle application.

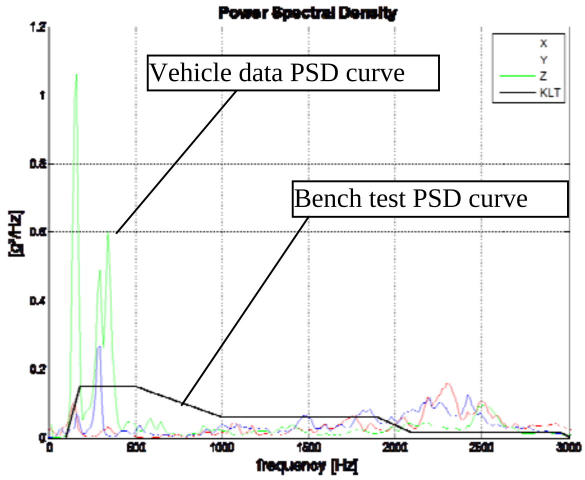

Figure 14: Generic bench test PSD and vehicle PSD

EXHAUST GAS MASS FLOW PROFILE

In most cases current vehicle applications do not provide optimum flow distribution due to packaging or NVH restrictions. The influence however on the thermal-mechanical robustness of a converter system should not be underestimated. Therefore it is important to account for severe uneven flow distribution when testing the durability of catalytic converters.

In any case a flow concentration located to the edge of the matrix has a negative influence on the mechanical durability of the converter. To simulate accelerated bias flow conditions during the bench test, the exhaust gas pipe and inlet cones directing the gas flow into the tested converter was designed accordingly.

Highly localized biased flow

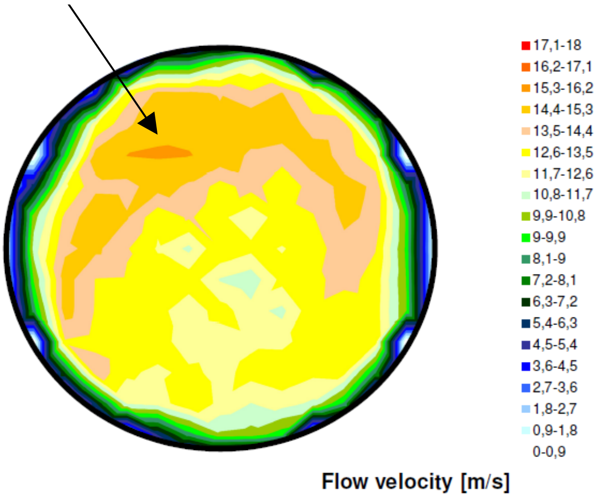

Figure 15: Flow distribution during bench test

Figure 15 shows high localized bias flow measured on the bench test during the baseline tests. The measured uniformity index [4] Gamma is 0,93.

The superposition of these severe levels of each single load type -temperature, vibration and flow- lead to a very high test acceleration factor.

To ensure a reproducible simulation of these high load levels, it was necessary to develop special test equipment.

TEST EQUIPMENT

EXHAUST GAS SOURCE

To simulate the thermal loads in the accelerated life test and to ensure that all current vehicle applications in the field can be covered, a new type of heat source was used [6].

This new burner system allows an independent control of exhaust gas mass flow and exhaust gas temperature and can provide rapid gas temperature transients of +15000 K/min and –8000 K/min and an exhaust gas mass flow change rate (dynamics) of +/- 200 kg/h per second can be achieved. Figure 16 shows the temperature/mass flow map of a burner, which is typically used for the test.

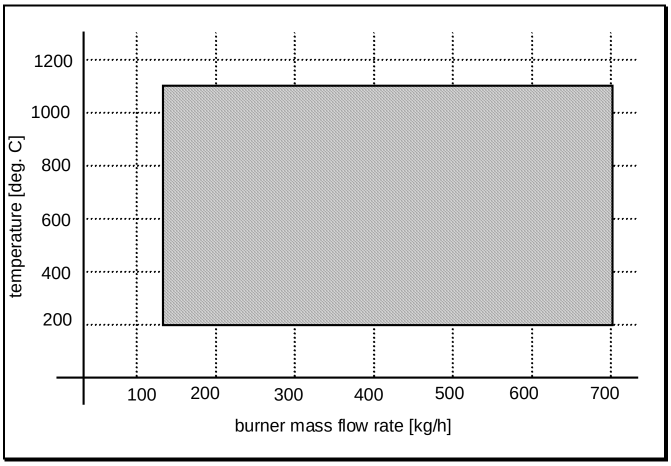

Figure 16: Temperature/ mass flow map of a gas burner used for the accelerated life test

VIBRATION SOURCE

The vibration of a vehicle application is typically a multi-axis load. To account for this effect, a two-axis excitation was required for the bench test. This was achieved by mounting the converter in an angle of 45° to the shaker vibration axis. The vector of force introduction is divided into to two directions: axial (X) and radial (Y). For Vibration control, accelerometers on water-cooled adaptors were used, which are directly mounted by welding to the converter mantle.

To ensure an introduction of vibration loads of 500 Hz and beyond to the test converter, a new very rigid and stiff fixture was developed which allows frequencies up to 3000 Hz. The schematic principle of the vibration introduction into the test converter and the accelerometer setup is shown in Figure 17.

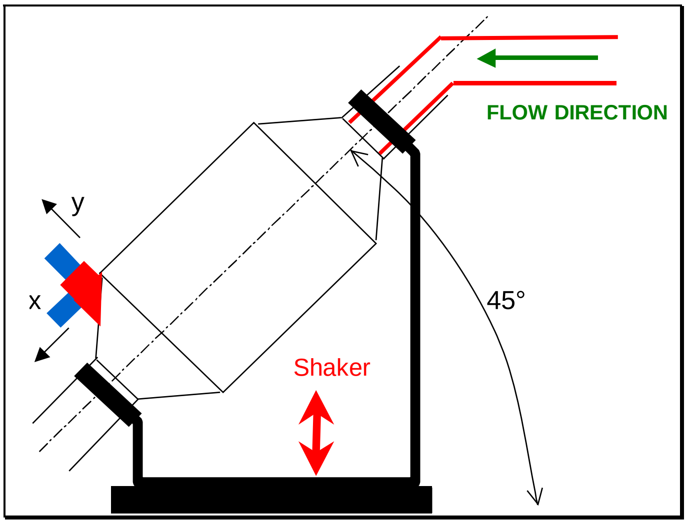

Figure 17: Schematic principle for load introduction.

TEST FIXTURE

To compensate for thermal elongations during temperature cycling, thermal expansion elements have been welded between the mounting brackets. The temperature control is done by thermocouples installed directly into the matrix. The flow distribution can be adapted by changing the angle of the welded inlet cone and adjusting the exhaust gas flow into the converter.

Figure 18 shows an example for mounting a round shaped converter to the shaker armature (moving element of the shaker). A patented slip joint is used to connect the exhaust gas pipes to decouple the gas burner outlet from the vibrating test part.

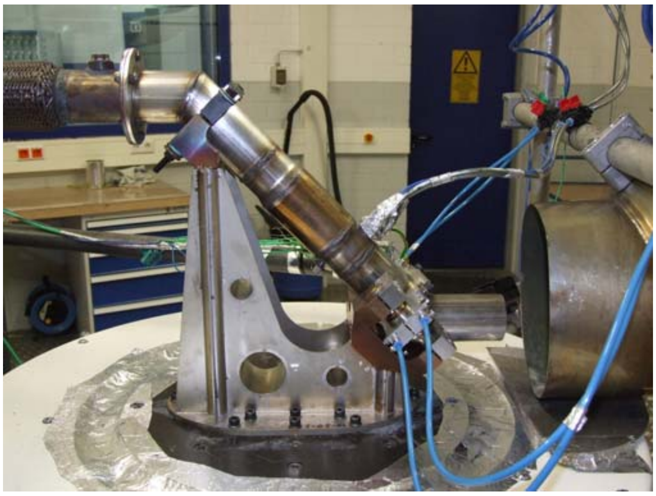

Figure 18: Example for a test converter mounting

ACCEPTANCE CRITERIA, ERROR STATE DETECTION

The basic mechanical function of the metallic catalytic converter is to retain the catalytic coated metal foil matrix (substrate) and to direct unrestricted flow of the exhaust gas from the exhaust manifold and/or down pipe through the catalytic coated substrate matrix to the vehicles exhaust system. To identify the onset of an error state or complete of loss of this mechanical function, a monitor system was developed, which allows continuous monitoring of the matrix retention.

It is assumed that any spring-mass system has characteristic signature. This means, that for a metallic catalytic converter test setup configuration any discrete frequency requires a defined input drive signal into the shaker to achieve the required PSD vibration level.

When failure in matrix retention occurs, the mechanical and modal properties of the test system (shaker table, fixture, converter) will change and cause a change of the specific drive signal (characteristic signature). For detection of function loss of the tested converter in the early stage (onset of failure) this shaker drive signal is monitored. Figure 19 shows an example how this signal (power or current) was used to detect a loss of retention (fracture) of the substrate during the baseline test.

The graph displays the inverted transfer function (ITF) between shaker drive signal and vibration output level vs. frequency.

$$1/H(f) = Output(f) / Input(f) \tag{1}$$

When an onset of fracture occurs, the input level for the low frequency significantly decreases. If the input signal reduction exceeds a predefined abortion limit, a matrix detachment is indicated.

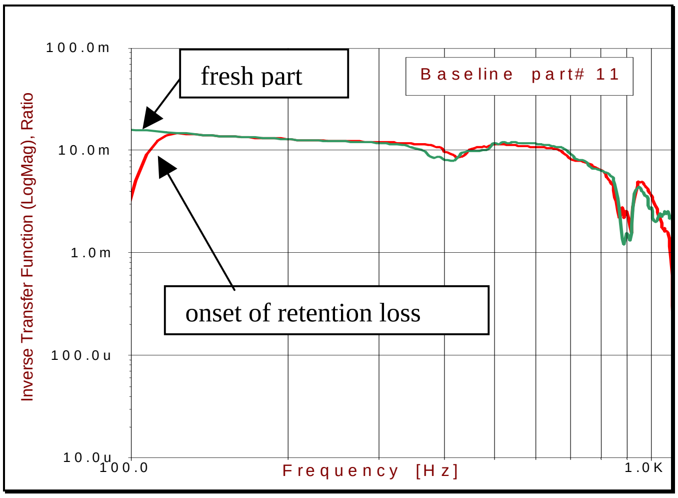

Figure 19: Example for matrix detachment monitored with ITF evaluation.

KLT RESULTS

The KLT test has been used to first verify the converter design.

Under the described test condition the substrates reached the end of life running time.

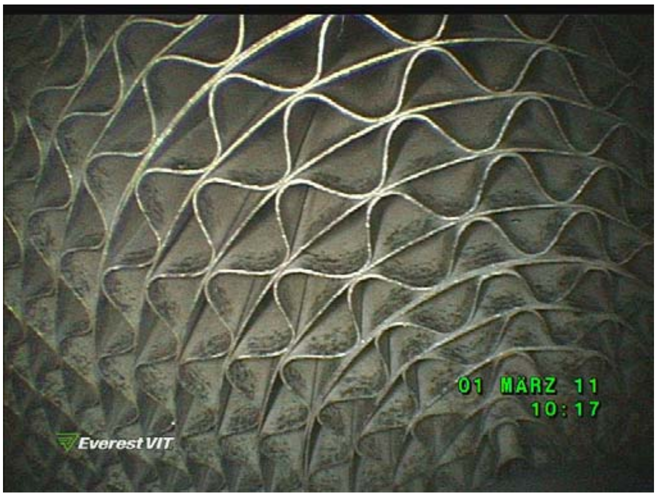

Figure 20: KLT Tested substrate, particular of gas inlet side

Figure 20 shows the gas inlet side of one tested converter after test end. It can be seen how the foils are in very good condition and the matrix is firmly attached at the mantle.

After this test the substrate can be tested under real life condition in a motorcycle.

DURABILITY TEST RESULTS

A proprietary test profile which includes high velocity part was used to test the durability of the catalytical converter.

The converters were then analyzed to deeply investigate the foil condition.

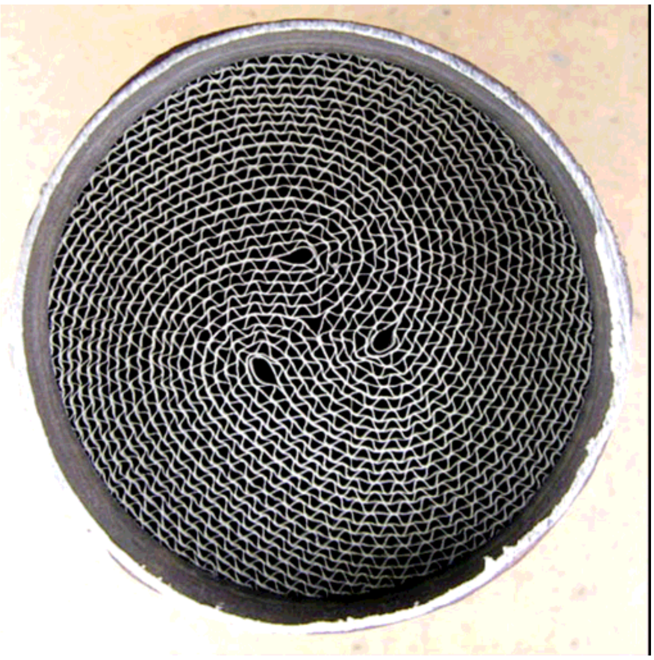

Figure 21: Tested catalytical converter

Figure 21 shows the gas inlet side of the catalytical converter after the durability test. It can be observed that the entire gas inlet side is in very good condition without any damage, i.e. no one of the two main failure modes (loss of matrix integrity, loss of matrix/mantle retention) is present.

In order to approve the substrate for serial production a further analysis in needed.

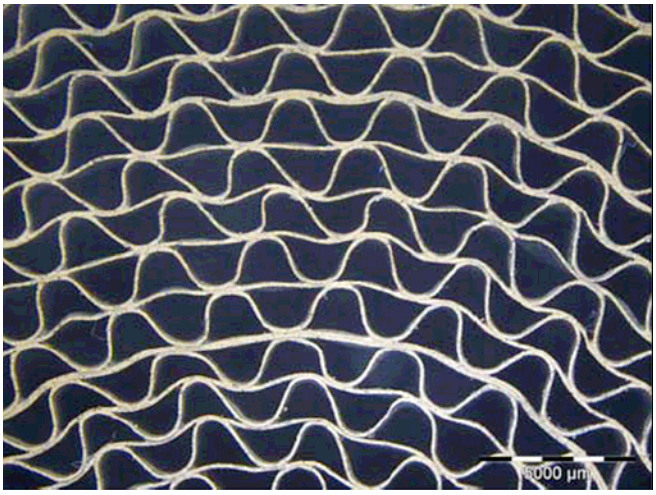

Figure 22: Tested catalytical converter, particular of gas inlet side

Figure 22 shows a particular of gas inlet face, moreover the analysis of the foil condition shows that no evidence of the principal stressors (Temperature/Temperature change rates, mechanical loads / frequency too high, poor uniformity index) can be observed.

SUMMARY/CONCLUSIONS

A new time and cost efficient accelerated component durability test was developed, which can account for the combined effects of critical stressors at a metallic catalytic converter.

The mechanical loads applied on the converter during the durability test are derived from a broad range of vehicle measurements.

An ongoing drive signal monitoring is performed to indicate the deterioration of the structural integrity of the substrate and its retention. This first indication is used to define further more frequent detailed inspections (i.e. optical) so that step-by-step details of the mechanism of function loss can be recorded for engineering analysis towards corrective actions.

A post mortem analysis, including macroscopically and microscopically documentation, was performed on tested parts to analyze and verify the function loss mechanism. This Analysis can be used for design improvements or other corrective actions.

It could be demonstrated that the new accelerated bench test can be used as a tool to discriminate between different matrix/mantle retention designs of metallic catalytic converters and to help the design engineer choosing the design that best fits the vehicle application requirements.

REFERENCES

1. T.Nagel, J.Diringer, 2000, "Minimum test requirements for high cell-density, ultra-thin wall catalyst supports, part1", SAE 2000-01-0495
2. K.Lange, S.Leggett, B.Baker, 2001, "Potential Failure Mode and Effects Analysis (FMEA) Reference Manual", AIAG, Southfield, Michigan
3. Nelson W., 1990, “Accelerated Testing,” John Wiley & Sons, New York.
4. Optimization of Catalytic Converter Gas Flow Distribution by CFD Prediction Heinrich Gillet GmbH&Co. SAE 930780
5. Development of Increased Test Conditions For Close-Coupled Catalyst Applications, T. Nagel, W. Maus, J. Breuer; Emitec GmbH SAE 962079, 1996
6. Entwicklung eines Alterungsverfahrens für katalytische und mechanische Dauerhaltbarkeit von Katalysatorsystemen für den Einsatz im Pkw
7. High Temperature Creep Behaviour of Ceramic and Metal Substrates S. Gulati, K. Geisinger, K.P. Reddy, D. Thompson SAE 9110374
8. Development of Metal Supported Catalytic Manifold Converter M. Asano, K. Yoshimura, M. Yasukawa, T. Takada, A. Onishi Toyota Engineering Technology Vol 40 No. 1

CONTACT INFORMATION

Lorenzo Pace
Technical Application
Emitec – Gesellschaft für Emissionstechnologie mbH
Hauptstraße 128
53797 Lohmar Germany
Email: lorenzo.pace@Emitec.com
Tel.: +49 2246 109510
Fax: +49 2246 109109

ACKNOWLEDGMENTS

The authors would like to thank Norman Fuss, Alfons Holzky, Nanette Ranke and Bastian Zerull, Emitec F+E Zentrum for the support during the test activities.