Whitepaper

Early failure detection on engines with multi-point vibration analysis

Use cases and advantages of a novel multi-point vibration analysis for early failure detection on combustion engines

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1 Introduction

Global competition leads to shortened product life cycles. The automotive industry is forced to release new models to the market in smaller intervals. Modern engineers have to deal with large reductions in product development and testing cycles, especially for engine durability testing; week or month long testing times become a major problem.

Figure 1: test stand for durability testing of combustion engines

By employing red-ant's MIG16 multi-point vibration measurement systems, red-ant has demonstrated a new way of economically reducing the higher demand for longer testing while concurrently allowing engineering professionals to gain more knowledge from a single durability test.

2 Systematical Description MIG16

Version 1.3 of the MIG16 measurement system was developed specifically for dynamic durability testing of engines. The unique multi-point vibration measurement enables the real-time monitoring system to detect and localize small damage at an early stage of the development testing. In that way MIG16 can significantly reduce the risk of large damage which will endanger the validity and value of durability tests and test stand equipment.

To achieve this, MIG16 digitalizes the dynamic signals (see section 2.1) with 100 kHz, 24 bit resolution ADC's and calculates so called NVH-Indicators in real-time. At the beginning of a durability test the characteristics of the NVH-Indicators are learned according to the defined testing profile (dynamic speed, torque, temperature, injection parameters, etc.) in a multidimensional matrix (see section 2.2). From these characteristics upper and lower limits are calculated using proven statistical methods.

This automated learning process has been optimized over the past 10 years using input and demands from MIG16 users and over 10.000 durability tests.

Initially, when a small defect develops following (in most cases) several hours of durability testing, a red-ant MIG16 SFE NVH-Indicator will indicate this defect. The NVH-Indicator (dynamic signal) will exceed the previously learned limit, generating a pre-alarm. All pre-alarms are checked against an expert system of logical rules (see section 2.3). In cases where the initial damage is so severe that continuing the durability tests would be dangerous, a shut-off signal is immediately delivered to the test stand.

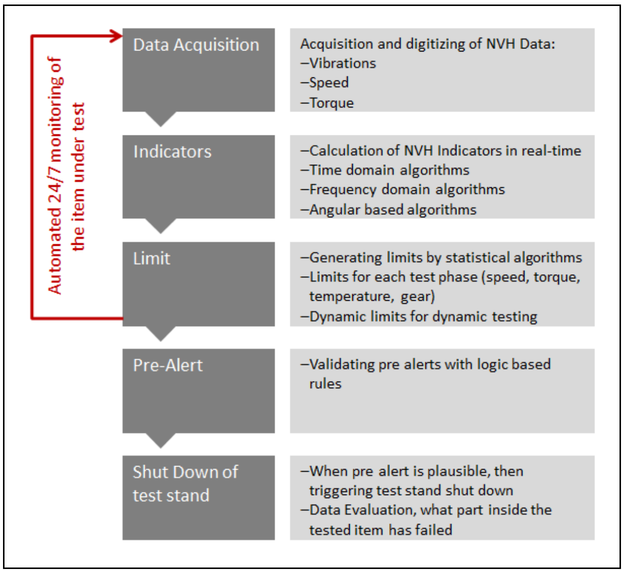


Figure 2: Process of the data acquisition and NVH-indicator calculation of MIG16

The general functional design of MIG is shown in Figure 2.

2.1 Measurands on the engine test stand

In addition to the vibration (acceleration) and crankshaft rotation speed, MIG16 will monitor/measure the test profile parameters (see Figure 2 and Figure 3). Vibration (acceleration) and the rotation speed signals are generally measured as sensor signals, whereas the test profile signals may be received as a serial digital stream via CAN Bus.

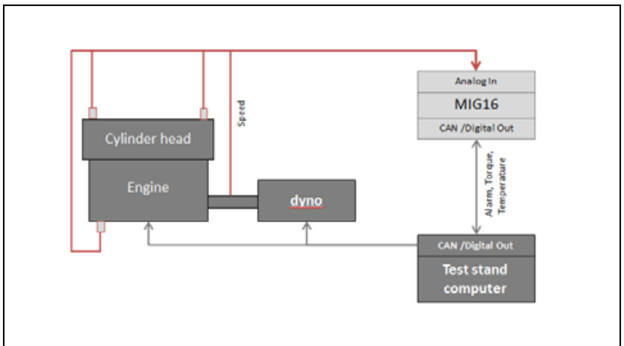


Figure 3: Signals for a MIG16 system at an engine durability test stand

It is important that MIG16 measures the vibration acceleration signals at strategically important locations: crankshaft housing and cylinder-head (see Figure 4 and Figure 5). Sensor location, ground isolation and cable management are important considerations. Red-ant engineers are postured to offer assistance in this important area, based on much experience.

Experts from our Engine Competence Centre will determine and document the exact position of the vibration sensors for each individual engine. The vibration sensors red-ant specify are especially designed for engine durability testing to withstand thousands of hours, high vibration levels (up to 5000 g), at high temperatures (up to 125°C) and deliver a linear frequency response over a wide bandwidth[1].

Engine speed signal is typically measured at the OEM crankshaft sensor. For this task red-ant has developed an electrical isolation amplifier that receives the either digital signals from Hall-sensor or the typical analog signal from an inductive sensor without interfering with the engine control unit (ECU). To measure the rotation speed direct at the crankshaft provides the user/engineering team another big advantage: MIG16 can analyze the torsional vibration according to the speed signal.

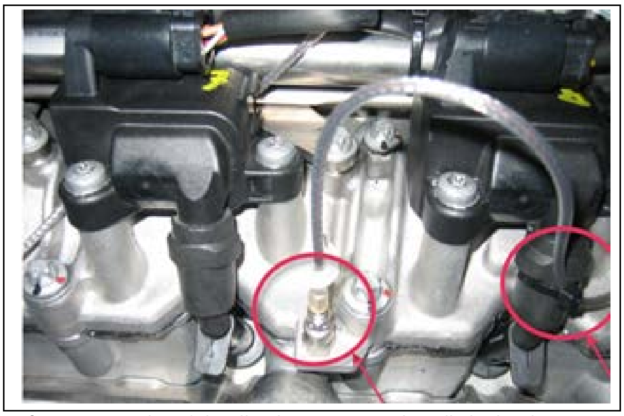


Figure 4: Location of the vibration sensors at the cylinder head

Figure 5: Location of the vibration sensors at the crankshaft housing

Beside the above named measurands, proper setup and configuration of MIG16 requires test profile information specific to the engine under test. These measurands are typically provided to the MIG16 computer via a serial CAN Bus from the test stand computer.

Out of the test profile measurands generally two are obligatory:

- Engine output Torque (calculated or measured)
- Engine Oil Sump Temperature

[1] Sensor types, that were designed for engine knocking detection (i.e. Knock sensor from Bosch or Siemens) are due to their technical specification, their relatively large size and weight not suitable for this measurement task.

The following test condition signals are optional necessary:

- Selected gear of transmission[2]
- Transmission oil temperature
- Injection Parameters
- Variable valve train parameters
- Parameter of the test stand controller, i.e. "activated blow by test phase"

Test shut-off signal from MIG16 to test bed computer is provided by three interface possibilities:

- CAN Interface
- Digital voltage signal 5 Volt TTL
- Relay contact

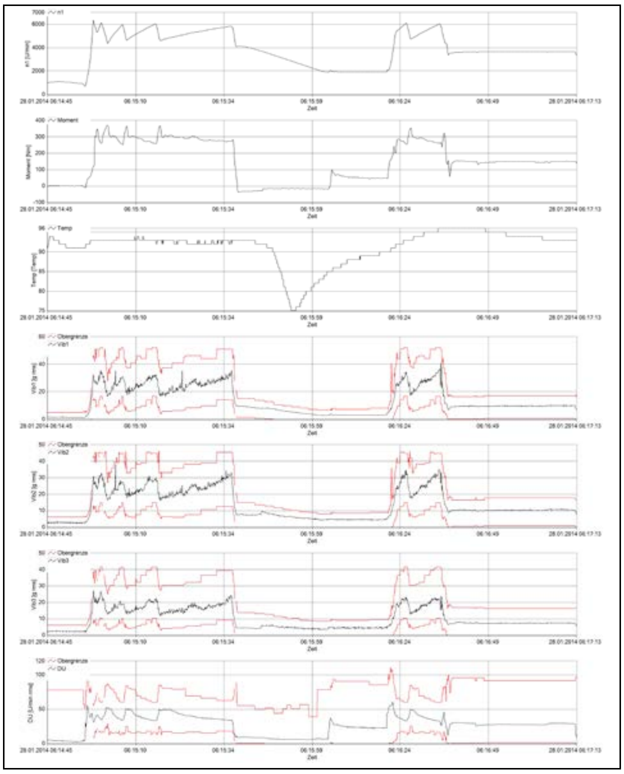
In addition to the above MIG16, provides Ethernet and Profibus interfaces. Utilizing one of these the automation of the measurement system can be quickly and simply programmed.

2.2 Calculation of the NVH-indicators

The NVH Indicators of MIG16 are calculated depending on the use case in three different domains:

- Time domain
- Frequency domain
- Angular domain

In the *time domain* the energy of the vibration acceleration signal for each measuring point will be calculated by digital band-pass filters and a root mean square algorithm. The term RMS-Value[3] is used for these NVH-Indicators.



[2] Only necessary if the engine is tested with a transmission.
[3] RMS = root mean square

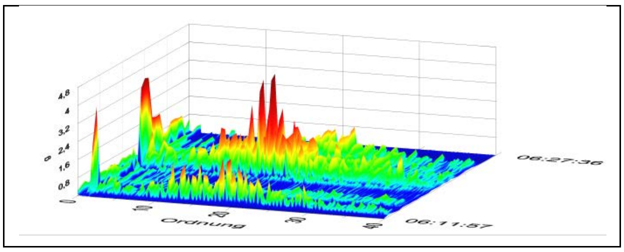
Figure 6: typical time lapse of a engine durability test with MIG16. Top-down: crank shaft speed, engine torque, engine oil sump temperature, NVH-Indicator RMS1 (cranks shaft housing), RMS2 and RMS3 (cylinder head front and rear), NVH-Indicator Speed fluctuation

The typical time lapse of the RMS-Value for three different points at the engine (multi-point) is shown in the Figure 6 in the graphs 4-6 (top–down). It is quite obvious to the reader that with rising engine speed the RMS-Values are also increasing. The red lines in the graph 4-7 are indicating the limits which were calculated during the initial learning phase.

In the *frequency domain* MIG16 is calculating from high resolution spectra NVH-Indicators, which are characteristic for a specific damage type. For this purpose algorithms of digital integration and FFT-Filters are used to extract an energy equivalent value from defined frequency ranges at multiple measuring locations (multi-point).

In the angular domain NVH Indicators are calculated that are in a defined ratio with the crank shaft. For this purpose the speed signal from a crank shaft sensor (i.e 60-2 pulses per rotation) is computed into a angular velocity signal. This signal is correlated with a mathematical model of the engine crankshaft speed in real time to gain an optimized angular velocity signal. From this optimized angular velocity signal new and finer sample instances (time and angular wise) are determined. Employing these mathematical perfected sampling instances the vibration signal is then digitally resampled. To solve the Antialiasing-Filtering problem and at the same time to gain a mathematical perfect angular equidistant sampling point from time equidistant sampled vibration signal, a method based on the "Kaiser Window", newly developed by and unique to red-ant, is used.[4].

In Figure 7 a MIG16 3D-orderspectrum and a 2D-orderspectrum of an Engine Durability test is shown. MIG16 delivers the highest orderspectrum resolution of all measurement systems currently available Early Failure detection systems on the market (128.000 Lines and 24 bit Amplitude).



[4] The traditional used methods, like hardware sampling or linear quadratic approximation, were not successful for the diagnosis. They only reached a signal to noise ratio of about 24 dB. Red-ant can reach with it new method a signal to noise ratio from larger than 96 dB.

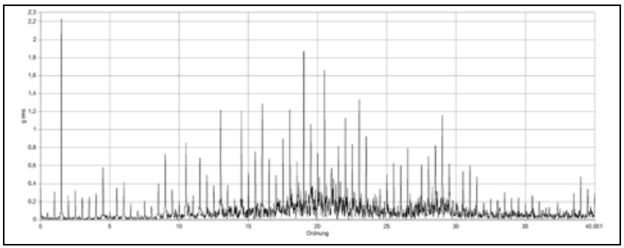


Figure 7: high resolution 3D- and 2D-orderspectrum of a combustion engine durability test.

To learn the normal behavior of signal amplitudes of the NVH-Indicators, MIG16 uses a classifier to group the test profile of the engine into intervals (see section 2.1). In this process each individual test condition is grouped into reasonable intervals. A sample classification with three dimensions of MIG16 is shown in Figure 8.

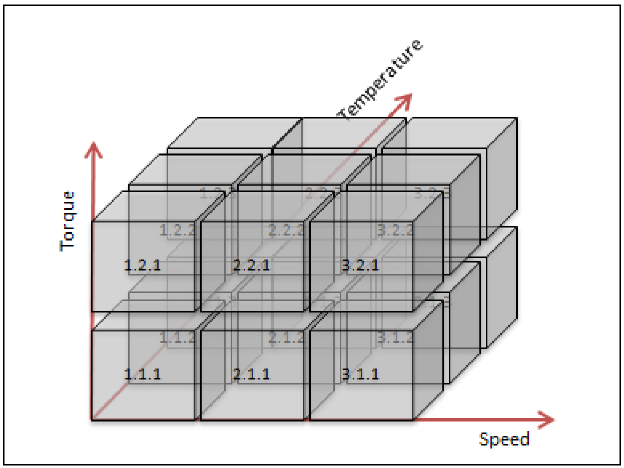


Figure 8: An example for a 3 dimensional classification of MIG16.

MIG16 provides capability to handle up to 12 unique dimensions for classification.

2.3 Shut-Off

To eliminate nuisance shut-downs of the durability test, the MIG16 System differentiates between a pre-alarm and a shut-off alarm. A pre-alarm will be released when a NVH-Indicator amplitude exceeds either a high or low learned limit. The pre-alarm is checked by the logical alarm manager software. If the alarm manger deems the pre alarm to plausible, the shut-off alarm is triggered.

The shut-off alarm is used to shut off the engine durability test stand in a controlled way, in an effort to prevent secondary damage on the tested article.

The plausibility check of a pre-alarm is based on the following logical rules:

- Amplitude of exceedance
- Counts of exceedance
- Duration of an exceedance
- class change distance

All parameters from the above rules can be adjusted to fulfill the customer's and the tested article's specific needs and requirements. The rules are generally connected with a logical *OR*, so if at least one rule is fulfilled, the shut-off alarm is sent.

With parameters of the first rule *Amplitude of exceedance* it is defined how large a single pre-alert is to trigger a shut-off alert. This rule is generally set up in a way that i.e. a single combustion knocking will not lead to a shut-off of the test stand, but on the other hand a fractured valve stem will reliably cause a shut-off alarm.

With the second rule *Counts of exceedance* the number of pre-alerts of a definable time span are counted. With this rule a MIG16 System can be setup that i.e. 10 Knocking events within in 15 seconds will lead to a shut-off alarm.

The third rule *Duration of an exceedance* is defining how long an exceedance, as the case may be not fulfilling the other 3 rules, can be, before a shut-off is triggered. With this parameter slowly developing damages like bearing damages can be precisely differentiated from short term vibration change behavior (i.e. variable-valve train errors, knock control settings).

The forth rule *class change distance* enables the user of MIG16 to ignore pre-alarms from determined transient behavior, like a gear change. In the set of parameter for this rule the timing before and after a class change (i.e. Ratio change) may be defined.

Supported by the high value of a logical plausibility check of pre-alarms, MIG16 became a tool which is very reliable and adaptable for highly dynamic test profiles of combustion durability tests.

2.4 Diagnosis

In the case of a shut-off of the engine durability test with MIG16, an automatic Report can be generated and released. This shut-off-report contains time stamping and the reason for the test shut-off. Additional trends of the NVH-Indicators and the time lapse of all measurands at the shut-off event will be reported.

These reports are typically reviewed and analyzed carefully by an Expert of the red-ant Engine Competence Centre in Munich and compared to an extensive Damage Database. Generally a short meeting via web-conference is held with all users and interested participants from the red-ant side and the customer side. In this meeting necessary next steps are discussed and defined. These steps are normally endoscopic evaluation of the defective part, oil check, sparkplug check, etc.

With the worldwide access of more than one hundred MIG16 Systems, that have documented several thousand defects the red-ant Engine Competence Center is in a position to analyze every possible defect in a very efficient, timely and effective way.

As engine durability test runs are generally continued throughout weekends and holidays, the red-ant engine competence center service is operating worldwide 7 days a week, 365 days a year.

2.5 Examples

The *first example* shows an engine durability test with a three-cylinder Engine. MIG16 shut off the test stand after 300 hours test time. The evaluation of the time lapse report (see Figure 9) shows a rising vibration level (vib 1, RMS-NVH Indicator) on a sensor that was located on the crankshaft housing, whereas no significant rise of the signal amplitude at the front and rear end of the cam-box is seen (vib2 and vib3). The exponential shape of the trend leads the diagnosis into the direction of a slowly growing mechanical failure.

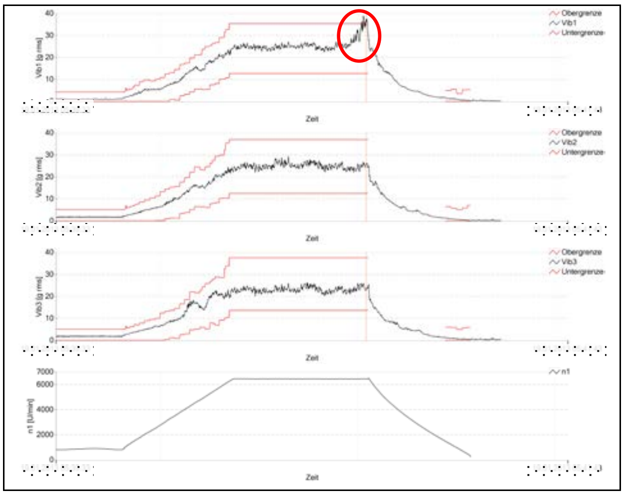


Figure 9: graph 1-3 are showing the MIG16 RMS NVH-indicator on crankshaft housing , cylinder head close by cylinder 1 and cylinder head close by cylinder 3. Graph 4 shows the speed of the engine during the test.

The direct following data evaluation from the red-ant Engine Competence Center revealed more evidence for a mechanical failure: A sharp rise of the vibration acceleration signal in the crank angle when cylinder 1 is firing (see Figure 11). Hence the beginning of damaged parts related of the crankshaft close to cylinder 1 was diagnosed. The test run was suspended and the engine was sent for disassembly and assessment.

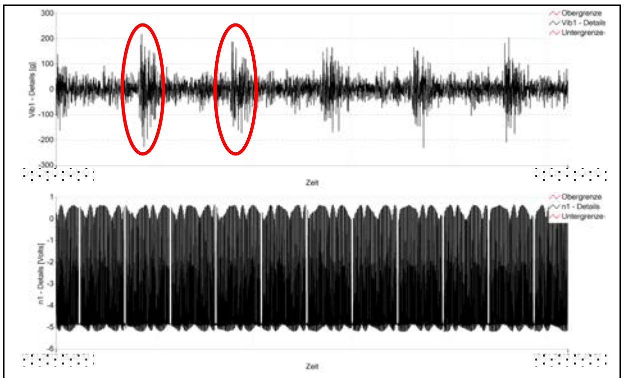


Figure 10: Top graph vibration acceleration as 24 bit/50 kHz Signal. Crankshaft angel signal from the 60-2 engine speed sensor.

The results of the assessment confirmed the diagnosis from the multi-point vibration acceleration measurement performed with MIG16: a starting crank shaft main bearing damage close to cylinder 1 (See Figure 11).

One of the bores in the bearing was found to be congested, causing a local reduction of oil pressure resulting in direct contact of the crankshaft journal to bearing surface. It is noted here that this damage was identified early enough to allow the customer to save the prototype engine, exchange the bearings and continue the test.

Figure 11: bearing half shelves for the 3-cylinder engine after a MIG16 shut off. Bearing number 1 shows clear abrasive marks.

The *second example* illustrates a 4 cylinder engine following approximately 400 hours of durability test time. MIG16 shut off the test because of multiple vibration events (see Figure 12). The events were identified at the measuring locations close to cylinder 1 and 2, and in smaller amplitudes also on cylinder 3 and 4 and with again a much smaller amplitude on the crankshaft sensor location.

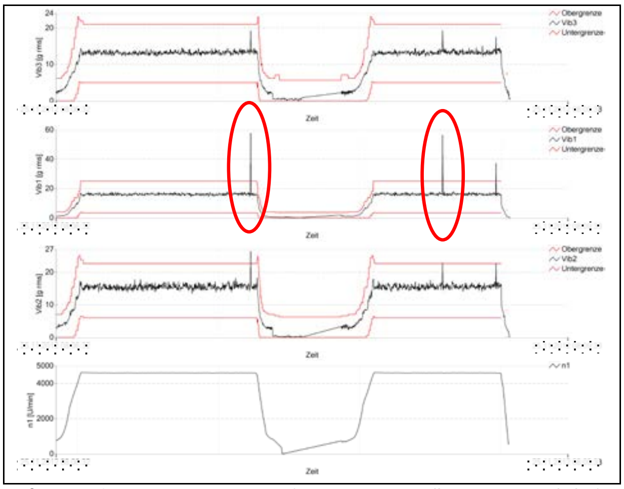


Figure 12: Top-Down: Lapse of MIG16 NVH-Indicator on crankshaft housing, cylinder head 1,2 , cylinder head 3,4, crank shaft speed

red-ant Engine Competence center analysis revealed that this signal content was caused by a extreme knocking event. This knocking energy was revealed in the measurement data of MIG16 shortly before TDC of cylinder 2 (see Figure 13). Based on the experience of the Engine Competence center database and the extreme vibration signal of up to 4000 g (peak to peak) a damage of other parts in the cylinder was expected. An endoscopy of the combustion chamber was recommended.

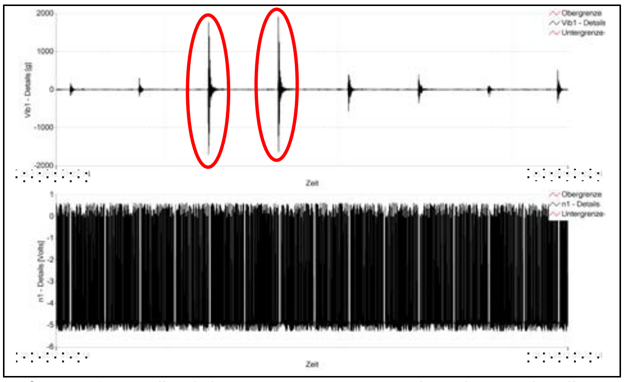


Figure 13: Details of the MIG16 measurement data close to the vibration event on cylinder number 1 and 2.

An endoscopy evaluation revealed early damage of the exhaust valve on cylinder 2. In Figure 14 the photograph of the exhaust valve is shown. Radial cracks can be seen close to the rim of the valve disk.

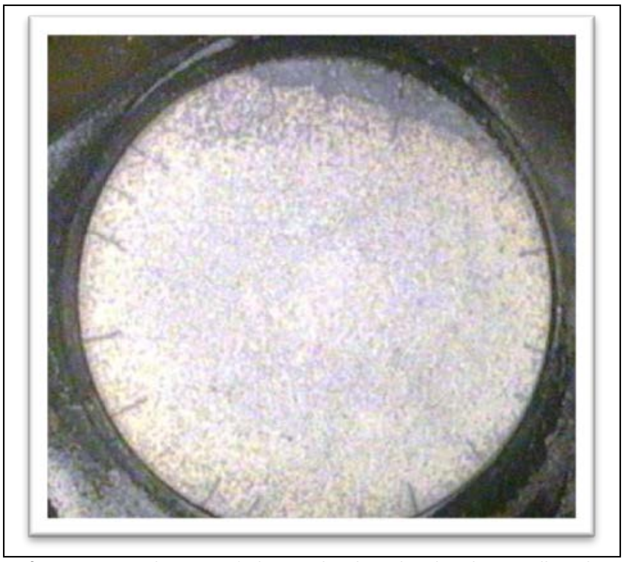


Figure 14: Endoscopy of the combustion chamber is revealing the MIG16 diagnosed damage: radial cracks on the exhaust valve of cylinder 2.

3 Conclusion

In both examples shown here and also numerous other cases MIG16 demonstrated repeatable capability of shutting off test stands and protected high content prototype engines from being destroyed. All these engines were in close to critical conditions, whereupon further testing would have caused severe secondary damages and possibly catastrophic failures. If that were allowed to occur then a mechanical forensic would be extremely difficult and root cause could be hidden by secondary failures.

The history and time of the damage could be read exactly from the MIG16 measurement data. Valuable knowledge for the tested engine construction could be safely gained with the help of MIG16 Data. Partly the shut off came in such a early stage of the damage development that the damaged parts could be exchanged and the test run be continued to gain more knowledge of other parts of the engine. By taking advantage of MIG16, invested capital (time and material of the prototype, fuel and test time costs) and test cell time was used much more effectively. In some cases, savings from a single test run that was protected by MIG16 was larger in magnitude than the initial capital investment into the MIG16 System.

The red-ant Engine Competence Center in Munich, which documents all MIG16 engine damages in a database, delivers all customers testing departments fast and reliable diagnosis and detailed information with regard to mechanical damage. This service allows testing operations to operate seamlessly on a continuous basis. By utilizing the support of the red-ant Engine Competence Center, which operates on 7 days a week, the downtime of large engine durability centers can be cut significantly, in some cases by 30% and more.

To live up to its role as an innovation leader on this particular market, red-ant continues developing the technology of early failure detecting for engine and transmission durability tests based on multi-point vibration analysis. Building on successes, a large benefit for red-ant customers is to obtain increasingly accurate diagnosis in shorter and shorter time frames.