URN (Paper): urn:nbn:de:gbv:ilm1-2014iwk-169:4

58th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 08 – 12 September 2014
URN: urn:nbn:de:gbv:ilm1-2014iwk:3

GEOMETRY- AND FUNCTIONAL PRINCIPLE IMPROVEMENTS OF HIGH-TEMPERATURE THERMOCOUPLES FOR IN-ENGINE MEASURING POINTS FROM THE VIEWPOINT OF THE FLOW AND LIFE OPTIMIZATION

Author: M.Sc. Axel Wodtke[1]; Univ.-Prof. Dr.-Ing. Klaus Augsburg[2]

- [1,2]TU-Ilmenau, Department of Mechanical Engineering, Automotive Engineering Group -

Keywords: exhaust gas, exhaust gas pulsation, exhaust gas frequency, sensor deflection, oscillation determination, load determination, high temperature thermocouple, thermowell, thermowell oscillation, compilation test rig, lifetime test rig

ABSTRACT

The reduction of emission limits and the efficiency enhancement of internal combustion engine commonly lead to an increase of exhaust gas temperatures. With the aim of making statements about motor function and component critical thermal conditions, the temperatures of the exhaust gas in particular are detected by highly dynamic high-temperature thermocouples with a thermowell. This measuring equipment is exposed to a very harmful environment and must be resistant and sensitive at the same time.

For this reason a novel test concept has been developed and implemented, which allows variable mechanical loads on a thermocouple with thermowell under realistic operating conditions, i.e. exhaust gas temperatures up to 1050°C. Numerous high load measurements have been carried out with this test rig resulting in a variety of sample failures, which were subsequently analyzed and discussed in details. This information can be used to develop the next generation of high temperature thermocouples with a better resistance despite dynamic measurement characteristics.

1. INTRODUCTION

As a result of emission limits reduction [1] and efficiency enhancement, the field of downsizing becomes more important and interesting for the automotive industry. Downsizing leads to higher engine speeds of combustion engines and to increased average temperature of the exhaust gas up to over 1050°C [2], particularly in charged petrol engines [3]. Such permanently high temperatures could be critical for components like the turbo charger, therefore more often high temperature thermocouples with thermowells are used to monitor the exhaust gas temperatures. For example, the engine load could be limited or the mixture could be changed, if a component critical temperature is detected for a determined time [3].

The appearing problem is that the temperature sensor itself is exposed to the component critical temperatures. Beside the high temperatures, the steady oscillations of the sensor tip caused by the exhaust gas pulsation are the main problems.

For conventional fields of application respective mainly steady flow, there are many rules, DIN standards, provisions and assistance programs to design a thermowell. For the area of a manifold, near the exhaust valve, it is more difficult to create an accurate sensor, which has a sufficient resistance against the harmful environment and is able to get a high dynamic measurement of temperature at the same time. If the thermowell is all too massive, the high dynamic process of temperature fluctuations could not be detected. In the exhaust there is a turbulent flow with a rapidly changing velocity field, depending on engine speed and load point. In combination with continuously recurring pressure pulses, a vibration of the thermowell will be brought about. The variable oscillations lead to a permanent stress of the material, which has a reduced strength under the prevailing temperatures.

The starting point for the improvement of the thermocouples with thermowell is to design a test rig, which allows testing a variety of different designs to examine and comparing them further with each other. The aim is to identify and correct any constructional faults at an early stage. On the test rig, it must be possible to simulate the real environmental conditions and loads from the inner side of a manifold. For the comparison of failure symptoms, it is advantageous when thermal and mechanical loads are separately adjustable. The mechanical stress should be able to be varied to initiate a sensor failure within an acceptable time frame, without achieving of unrealistic values. The thermal stress of the investigated sensors during the whole testing procedure must be maintained constantly at the temperature limit which is critical for the component, in order to generate the potentially harmful effects. With the developed testing method it is possible to examine the effects of exhaust gas pulsations influencing on the thermowell of a high temperature sensor among other factors, which would be set up permanently, for example, at the full motor load.

2. SENSOR OVERVIEW

Figure 2.1 shows on the left side two generations of an exemplary high temperature sensor for in-engine temperature measurement. Generation *B* in this case is the advancement of the generation *A*. On the basis of tests of the older version on the test rig, design improvements could be developed and implemented in the new generation, which was then tested for comparison as well. Based on these sensors, the operation of the test rig, the determination of the mechanical and thermal stresses and the evaluation of failure symptoms are presented below.
It is in both cases a Type *N* thermocouple, whose wires are protected through a high strength steel thermowell against wear. The *NiCrSi* and *NiSi* wires are embedded in a powder-like oxide, which must have a certain density in order to optimize the heat transfer from the thermowell to the wire connection. Both versions have a thin tip to improve the heat transfer to increase the dynamics of the sensor. The sensors have been mounted in the exhaust manifold in each case by a union nut.
On the right side of figure 2.1 simplified schematic diagrams of these sensors are shown, in which the fundamental differences in the design can be seen. The older error-prone sensor has a continuous thermowell with a laser-welded mounting collar and the new version has a thin continuous thermowell with mounting collar of body sheet. This body sheet also has the task of protecting and supporting the inner life.

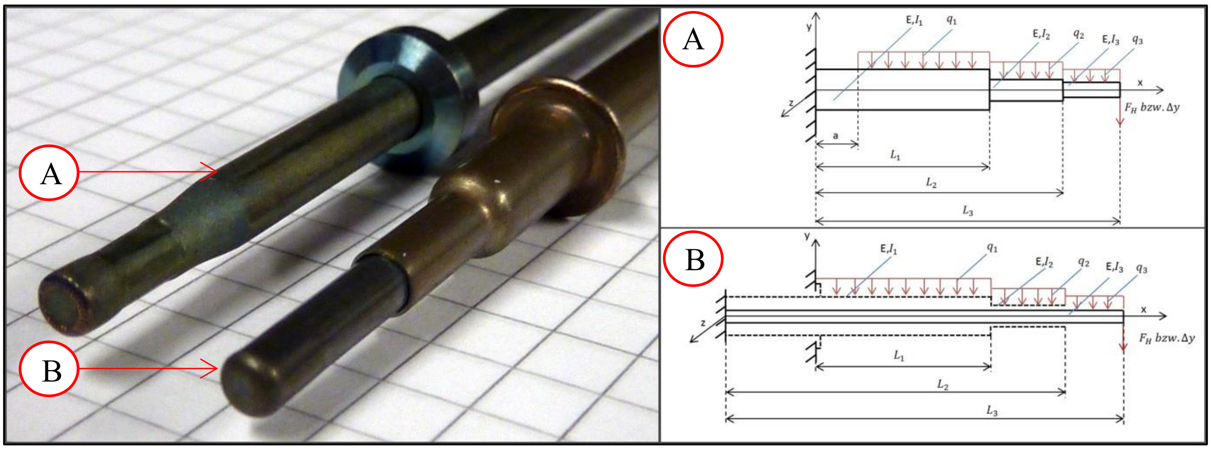

Figure 2.1: Example of two high temperature Thermocouples with thermowell (A-old one / B-new one)

With reference to the schematic drawing it can be seen that not the whole thermowell of the new sensor exposed to the exhaust gas flow as with the older version. Thereby the new one could be constructed thinner. In addition the length was changed, which may bend due to vibrations. The support of the inner life prevents an accidental increase of deflection and thereby damages the thermowell. So the new mounting collar of body sheet ensures a better distribution of the applied forces and moments.

3. DETERMINATION OF THE LOAD

To develop a test rig for an endurance test of a high temperature thermocouple with thermowell, several boundary parameters have to be known. They are divided into thermal and mechanical loads.

3.1 Thermal loads

The temperature indicated by a thermocouple with massive thermowell is in the most cases not exactly the real temperature of the exhaust gas in the exhaust manifold. It happens due to the fact that the manifold is usually cooler than the exhaust gas flow, because the manifold is cooled by the ambient air. Considering this fact a heat transfer of the flow to the manifold ensued and the thermowell operates as a heat conductor. In certain cases this effect can also be reversed. This measurement error is compensated by several electronic devices. To get the real thermal loads on the thermowell tip, a high-speed thermocouple was used. This has an extremely small thermal mass, which means that it can detect temperature oscillations. It is shown in three magnification steps in the upper part of Figure 3.1.
The investigations were carried out on a 4 cylinder petrol engine dynamometer at the Department of Mechanical Engineering / Automotive Engineering Group at the Ilmenau University of Technology.

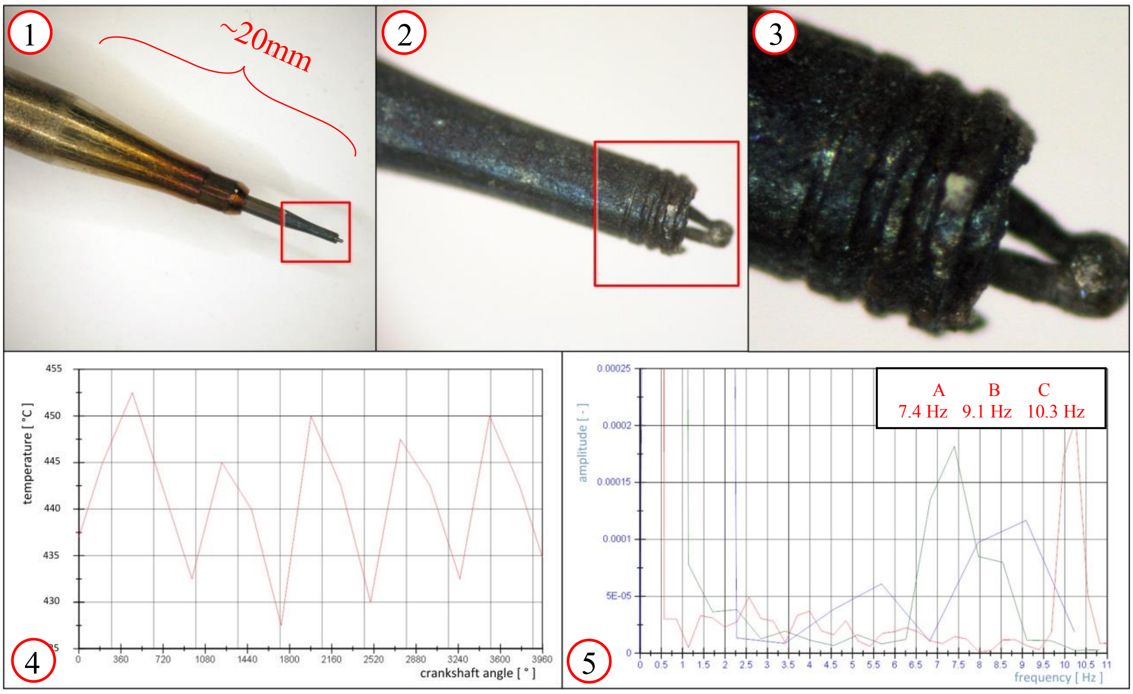

Figure 3.1: 1 – ultra thin thermocouple for high speed measurement; 2 – enlargement of marked area in 1; 3 – enlargement of marked area in 2; 4 - oscillation of temperature in one exhaust outlet at constant rpm and without load; 5 - FFT-Analysis of tree temperature-signals at A-848 rpm ; B-1025 rpm; C-1519 rpm (all without load)

These temperature measurements could be performed high dynamically, thereby temperature oscillations, initiated by the periodically opening and closing exhaust valve could be detected. Because the exposed measuring point is very susceptible to damage the tests were carried out at comparatively reduced stress levels. For a low load case the oscillations in gate 4 of Figure 3.1 are shown. In section 5 an FFT analysis of different temperature signals is shown at different constant engine speeds, which correspond to the respective frequencies of the exhaust valve ports. The comparison of the temperature measurement by means of high speed thermocouple with a conventional sensor element results in an increased temperature detection of up to 70 ° C. For testing with the test rig this means that the desired temperature must be higher than the temperature detected by the test sensor. Therefore, the temperature of the thermocouple test rig is set by an additional thin control sensor. In addition to the weakening of the component strength due to high temperatures, there is a further danger from the temperature input, the problem of the recrystallization of the thermocouple wires. In order to strengthen the influence of oxygen inclusions on possible chemical reactions inside the thermowell, the tip of the thermowell can be drilled without violating the thermocouple wires.

3.2 Mechanical loads

The flow in the exhaust is characterized by temporally and geometrically highly dynamic processes. This behavior are, among other things, the mass flow distributions, temperatures, pressures, densities and flow velocity that are more or less interconnected. The mechanical stresses can lead to destruction of the thermowell, based on the interaction of these turbulent flow characteristics. Figure 3.2 is demonstrating an exemplary flow velocity distribution of an exhaust gas manifold. In this example it is shown that exhaust speeds over of 500 m / s, as a function of engine speed, load, and geometry, etc. are possible. Due to the transient character of the parameter and the turbulent flow, relevant vortex shedding cannot be formed and their effect is not relevant. The constant speed changes would prevent the occurrence of a stable vortex street behind the sensor, thereby it can be assumed that the possibility of occurrence of relevant vortex shedding frequency is prevented. That there can be negative mass flows in this system is shown in Figure 3.3.

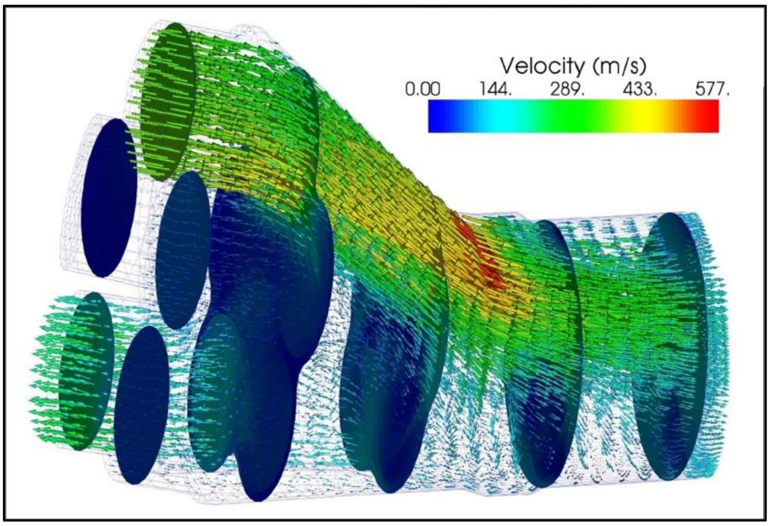

Figure 3.2: distribution of flow velocity in a 5 to 1 junction [4]

Due to the highly dynamic processes in the exhaust manifold, it is important to check a possible correspondence of the sensor natural frequency with the frequency of exhaust gas pulsations, as normal with the vortex shedding frequency in other flow situations. In both cases it is of interest to avoid the resonance frequency in order to prevent an increasing of the amplitude. Measurements have shown that the deflection of the sensor tip, as a result of the exhaust gas pulsations, achieved a significant value even without effects of resonance. For an initial assessment to determine the mechanical loads and effects it is possible, by means of known methods of calculation with for example the resistance torque and drag coefficient of the simplified Senor model, shown in Figure 2.1 and a mass flow rate respectively velocity distribution as shown in Figure 3.3. to estimate the deflection of the sensor tip.

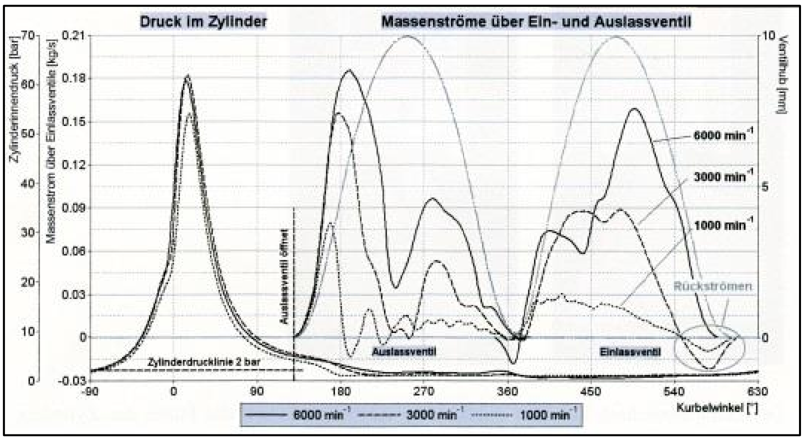

Figure 3.3: exemplary distribution of mass flow in outlet valve [5]

In order to identify and investigate a real amplitude response a lot of attempts have been carried out by using a blue laser triangulation measurement. By that it succeeded to investigate and capture the deflection of the sensor tip under real conditions. This measuring method also provides the possibility to get diverse conclusions about the oscillatory behavior of the sensors. In figure 3.4 an exemplary oscillation of a senor tip from Generation A is shown.

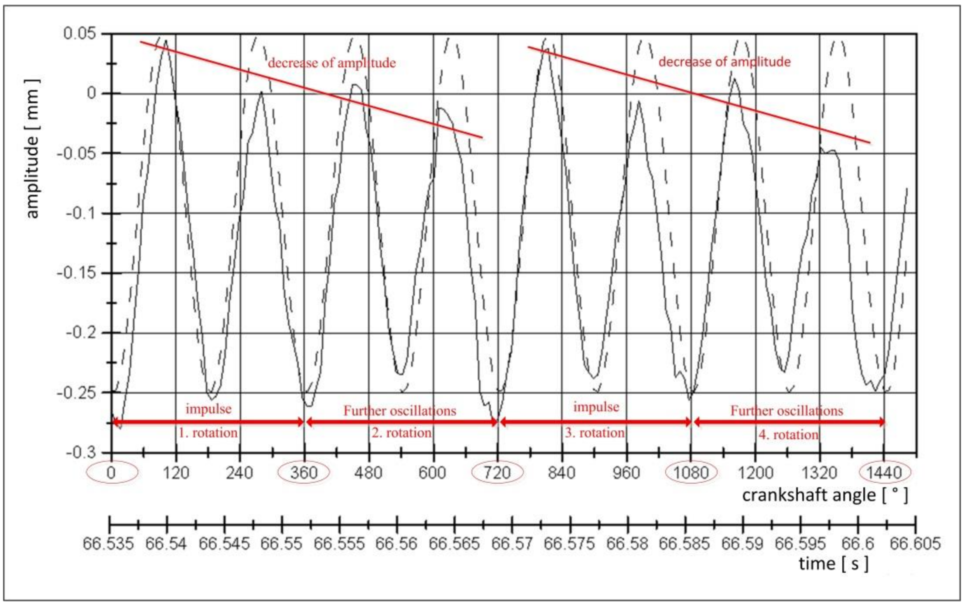

Figure 3.4: oscillation amplitude of the sensor tip at static engine speed of 3550 rpm (closed line: laser triangulation measurement, dotted line: corresponding simulation line on test rig)

The laser triangulation system was positioned so that it detects only the sensor motion in the flow direction. Furthermore should be considered, that possible lateral movements by engine vibrations or something else can not disturb the measurement. The laser senor was connected to the exhaust manifold, thus ensuring an equal oscillating system was created. Through a little opening in the manifold, it was possible to create an unobstructed path between the laser sensor and thermocouple tip. The measurement was performed a few centimeters behind the opening of an outlet channel from the engine block. The fixing of the sensor was performed according to the specifications with union nut and specified tightening torque. All

experiments were performed at several speeds, which were held constant in each case over a long period of time.
Due to the laser measurements the vibration behavior and a corresponding deflection of the sensor, to show an amplitude magnitude, could be determined by realistic load. In the figure 3.4 can be seen, that the sensor has a continuous oscillation behavior, even though the time sequence without boost from the exhaust stroke while the rotations when the exhaust stroke is closed. The intermediate amplitudes are reverberation effects. This is also confirmed by a continuous decrease of the amplitude, which is only distorted by overlays. The vibration of the sensor tip is similar to a sine wave having an offset. This offset is to lead back to the adjustment because it was still there even at engine speed zero after the test series. Based on the time scale can be concluded the present frequency. An FFT analysis confirms the first assumption, the sensor frequency is constant at a constant engine speed. By means of the FFT analyzes of several laser measurements could be shown that the oscillation frequency of the sensor is directly associated to the engine speed and the mass flow profile respective the velocity profile.
The frequency of the range which is shown in Figure 3.4 is 119 Hz at a constant engine speed of 3550 rpm. For high speed temperature measurement, shown in Figure 3.1, follows according a FFT analysis a corresponding frequency of 7.4 Hz at a speed of 848 rpm. Relating to the temperature measurement it can be say that two rotations of the crankshaft, one increase in temperature occurs, which is a half per rotation. For the path measurement results a continuous value of two peaks per rotation of the crankshaft. These consist of pair-wise forced vibrations or further oscillations when considering the pulses in one flue.

Based on these results, the following calculation gives a possibility to determine the frequency of loads, caused by pulsations of the exhaust gas on a sensor in the exhaust manifold.

$$f_{tc} = \frac{n*p}{60} \qquad \text{fo.1}$$

$f_{tc} = \text{frequency at the thermowell (temperature or deflection)}[\text{ Hz }]$
$n = \text{engine speed } [\text{ rpm }]$
$p = \text{peak per rotation of the crankshaft } [-]$

The application of the equation, with p equal to two, for the vibration calculation assumes that the pulsation has a clean double peak expression as shown in Figure 3.3 in the exhaust manifold. Concerning the temperature it is assumed that the temperature fluctuations are still clearly measurable. So the peaks must not be distorted by overlays or other effects in both cases. Under this assumption, for the exemplary temperature measurement at 848 rpm an calculated frequency of 7.1 Hz and for laser triangulation measurement at 3550 rpm, an calculated frequency of 118.3 Hz results. This means in conclusion, that from this type of temperature and vibration measurements in the exhaust manifold can be concluded on the engine speed. According to the measuring possibilities there will be limits for the accuracy and usability at high speeds, for example through overlay effects of several exhaust ports or by scanning speeds or measurement accuracy.
To obtain information about possible feedback effects between excitation frequency and natural frequency, a laser vibrometer had been used, as shown in Figure 3.4. The influence of the tightening torque on the natural frequency could be detected by a test series as not relevant, however the lowest moment was set at realistic 20 Nm. The increase of the torque was carried out until stagnation of the low frequency changes at 25 Nm (generation *A*). The results show that there is no accordance between the natural frequency and the vibration

frequency of the sensor tip in the manifold, which is stimulated by the exhaust pulsation of one exhaust valve.

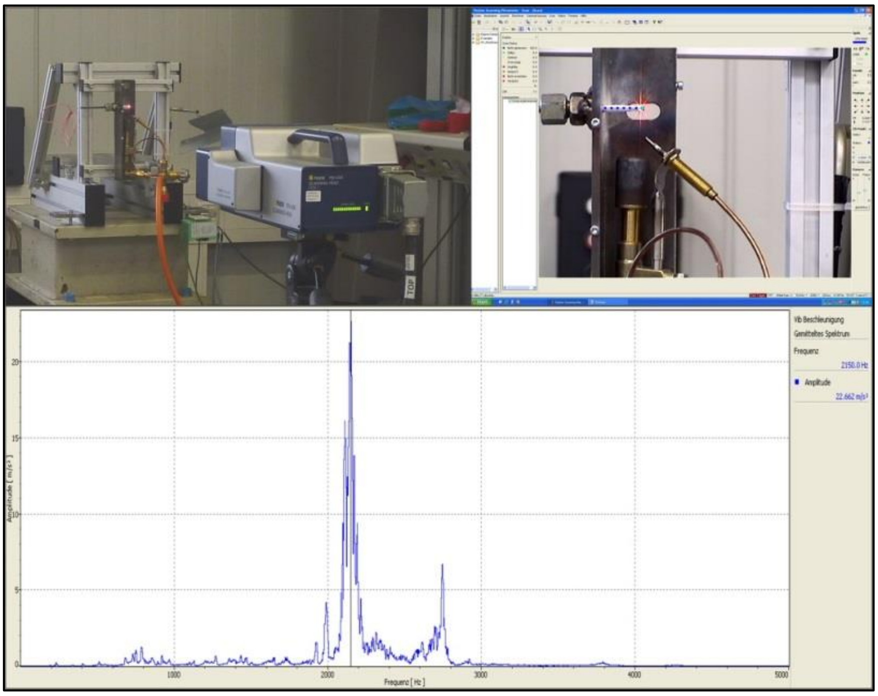

Figure 3.4: measurement of the natural frequency of sensor generation A by means of laser vibrometer measurements

4. TEST RIG IMPLEMENTATION

Using the previously defined limits for frequencies, amplitudes, and maximum occurring temperatures, the operating principle of the implemented test rig was developed. The functional diagram for showing the operation of the created "comparison test rig" for high temperature thermocouples with thermowell is shown in Figure 4.1.

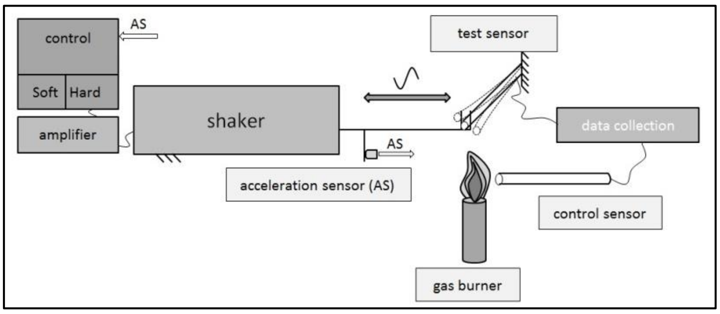

Figure 4.1: principle of the sensor test bed

The test rig allows the simulation of the effects of exhaust gas pulsations on thermocouples with thermowell, by initiate a deflection of the sensor with any amplitude and any frequency at the desired temperature. If the parameters of frequency, amplitude, and temperature, are chosen realistically, an estimation of the lifetime of different sensor generations is possible. At a magnification of the parameters, a faster aging of the sensors is achieved, thereby in a very short time a variety of failure symptoms can be achieved.
The sensor deformation is initiated via a clamp which is connected to a shaker. Shaker frame and test sensor are connected to each other via the base frame. The clamp is designed to be

thin in order to generate a sensor deflection realistic as possible and can be seen in the next figure.

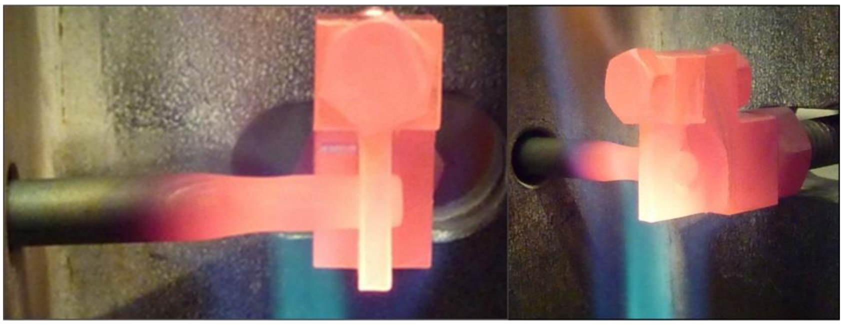

Figure 4.2: clamping of the sensor tip

The whole test rig without the software and control units is shown in figure 4.3. In the figure it can be seen that the temperature is generated by a gas burner. This temperature generation and entry in the sensor is similar to the normal exhaust gas, compared to maybe an electrical generated temperature. In accordance with the requirements of current sensors in the exhaust passage, temperatures over 1050°C may be generated.

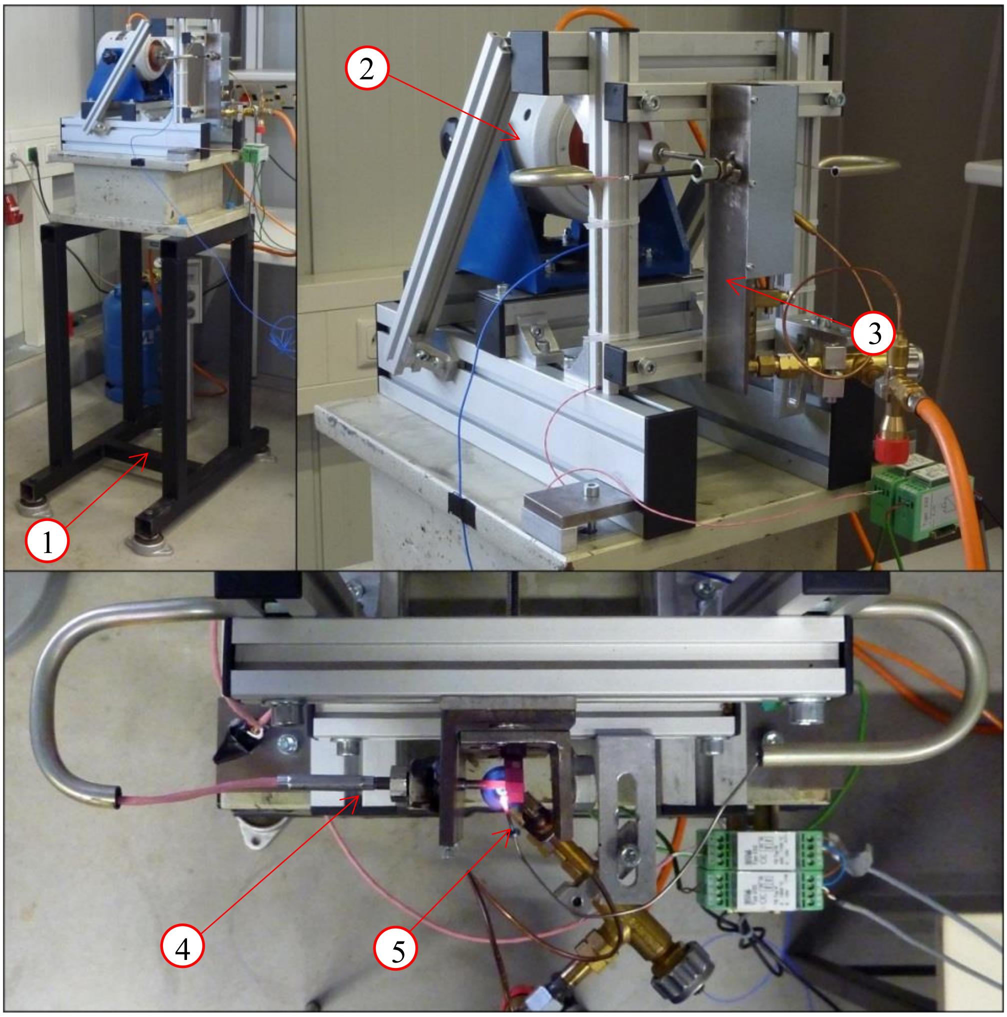

Figure 4.3: sensor test rig: 1-base frame; 2-shaker; 3-test sensor; 4-control sensor; 5-gas burner

As stated above, a temperature control sensor has to be used to adjust the temperature of the gas flame, because the heat dissipation of the thermowell by clamping and mounting with the union nut, is very high. For the control sensor a very thin and long thermocouple was selected which does not have a strong connection to the frame, thereby the detecting of the real gas flame temperature is more correctly. The regulation of the gas burner has a coarse and fine adjustment, so that a desired temperature can be precisely adjusted. The base frame must be designed very stable with vibration damper in order to minimize transmission of vibrations into the ground.

5. INVESTIGATION AND KNOWLEDGE

5.1 Failure symptoms

The aim of the investigation from sensor generation *A* was to discover a multitude of possible vulnerabilities in order to fix them constructively. The amplitude is determined relative to the real case, and doubled in most cases to increase the failure rate, which results in this case, that the tests includes no information about the sensor life time, but the basis for comparison of different sensor types and configurations is produced.
As simulation frequency the frequencies were, among others, according to the formula fo.1 selected to 100 Hz and 150 Hz, the test results are shown in Figure 5.1. At a subsequent sensor placement in the vehicle, this would be an engine speed of 3000 rpm or 4500, if the incident flow is done by one or two cylinders with appropriate timing. The test oscillation mode corresponds to a sine wave, see Figure 3.4. The comparative values of the subsequently developed generation B is also shown in Figure 5.1. The maximum test time was set at 20 h, whereby a frequency-dependent maximum number of cycles arise.

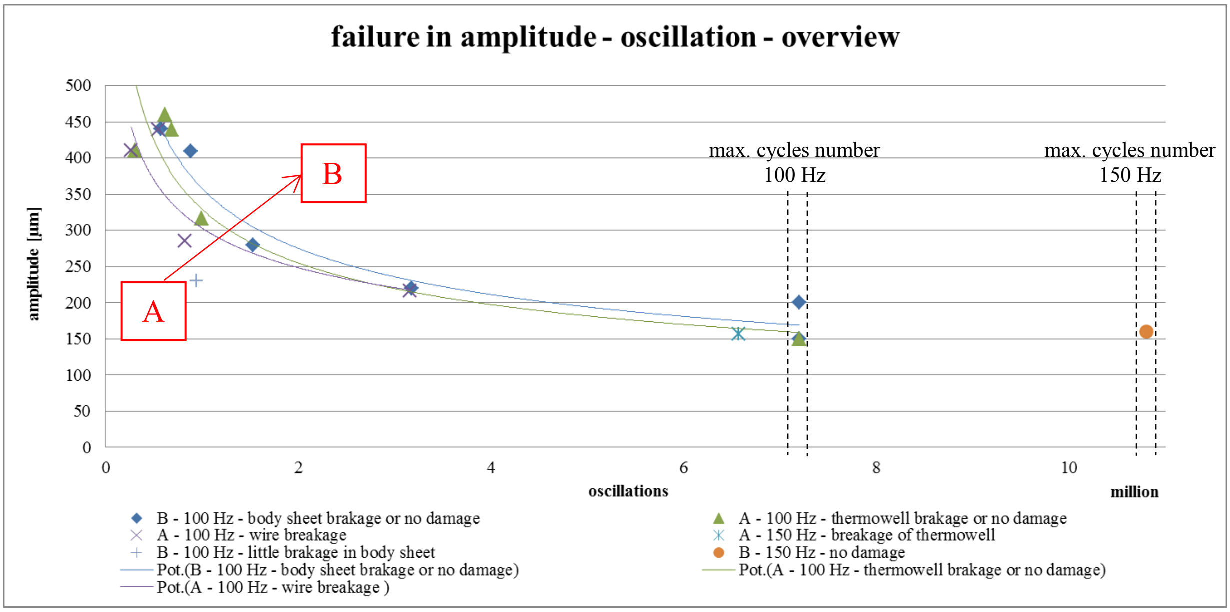

Figure 5.1: failure symptoms and oscillations

The two worst damage of a high-temperature thermocouple with thermowell is the breakage of one of the two thermocouple wires, causing an immediate loss of a usable temperature signal or on the other a breakage appearance in the thermowell. In the worst case this might destroy the thermowell and lead to a fall in in the manifold, which in turn can damage or even destroy other components such as the turbocharger. As shown in the graph above, a marked reduction of the deficits in the second generation had been achieved. In particular, the occurrence of a thermal wire breakage could not be detected in the more advanced generation. Generation *B* compared with *A*, shows inter alia a significant improvement of operating life in terms of low amplitude at high frequency. At higher test amplitudes there is no breakage in the thermowell, but in the body sheet. This failure symptom was, however, at higher cycle numbers as the breakage of the thermowell in generation *A*. It had been designed differently, in a further development step toward generation C.

5.2 Detection

By permanently forced vibration, resulting a thermal wire breakage during the test, not in a complete breakdown of the temperature signal, but is like an uncontrolled temperature oscillation of several hundred degrees Celsius. The reason for this is that the ends of the broken thermocouple wire, depending on the vibration, sometimes have contact and so an electrical contact is made and a thermoelectric voltage can be transmitted. Figure 5.2 shows the temperature profile of test and control sensor during a test. It is recognizable that the temperature signal of the test sensor has considerable fluctuations after 21 minutes, but the temperature signal of the control sensor remains mainly constant.

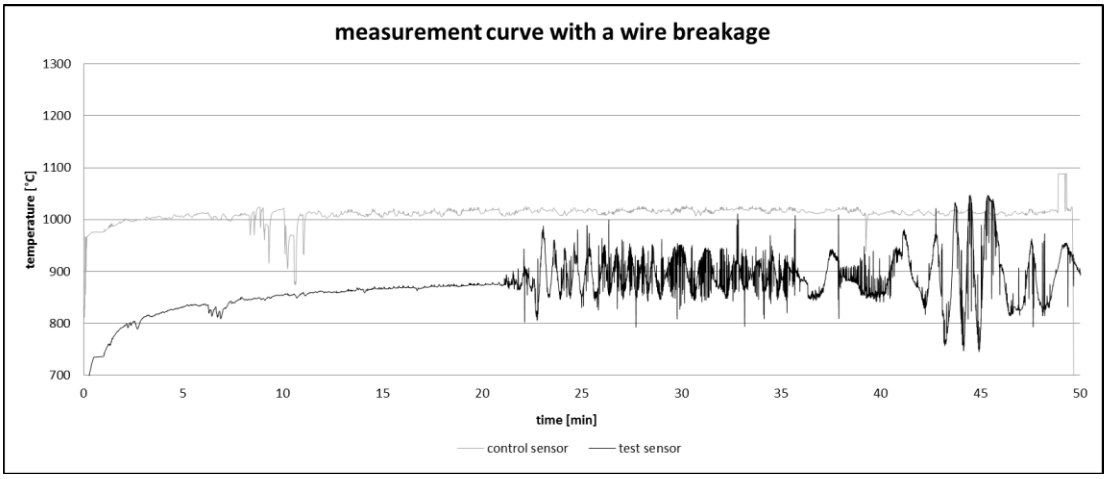

Figure 5.2: measurement of the natural frequency

It is also seen that the average temperature of the control sensor is about 100 ° C higher than of the test sensor. This confirms the heat dissipation by clamping of the thermowell tip and mounting in the base frame. The thermal load of the thermowell is still sufficiently high, because in this case the ambient temperature is crucial. The occurrence of a breakage in the thermowell of the clamped sensor results in a decrease of the required shaker performance and can be detected. In addition a change in frequency of the vibration noise is perceived at an early stage of breakage and can be controlled by a test interruption including visual inspection.

5.3 Hereinafter investigations

To check if the crack phenomena of the second generation only affect the body sheet and not in addition, the thermowell, X-ray investigations were carried out. These were carried out by means of computer tomography from the Innovation Center of Mobility from the Free State of Thuringia. The following overview shows some of the possibilities of visualization using this high-resolution imaging method for non-destructive material testing. Pure x-rays and computer-generated geometries are shown. It follows that no breakage development in the root zone of the thermowell occurred, only a significant breakage growth has occurred in the body sheet.

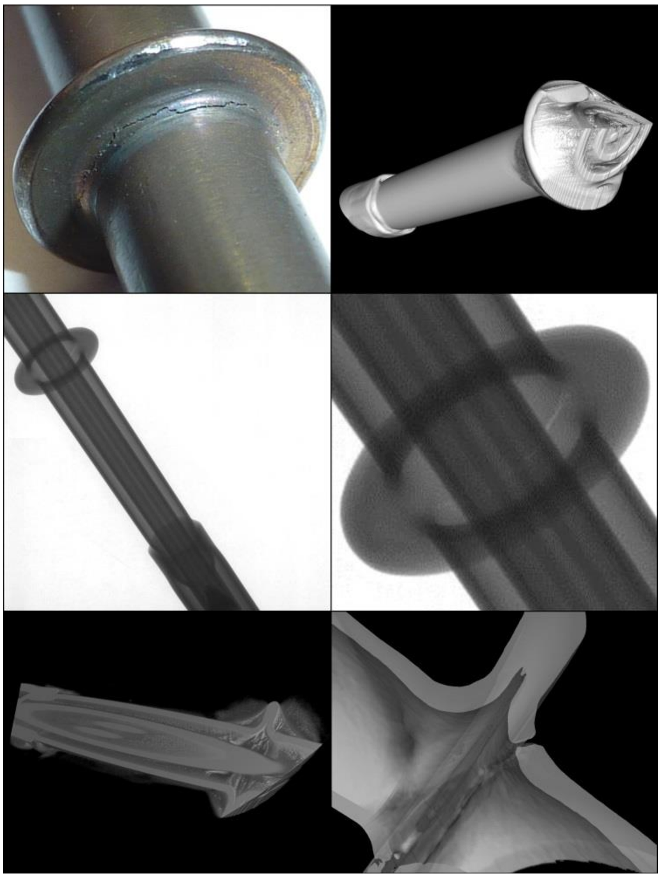

Abb. 5.3: computer tomography images of a sensor with a breakage in the mounting area

Another however destructive material testing method for breakage propagation investigations of different design versions of thermowells is light microscopy. Figure 5.4 shows a longitudinal section of a sensor of Generation *A*. On the right side is a magnification of the area being marked in the left screen. It can be seen that the breakage occurred in the thermowell itself, but also on the laser welding of the mounting collar. This leads to the conclusion that the laser welding of the mounting collar of Generation *A* implies a possible weakening of the material properties, which is inappropriate to mount the sensor and should be modified.

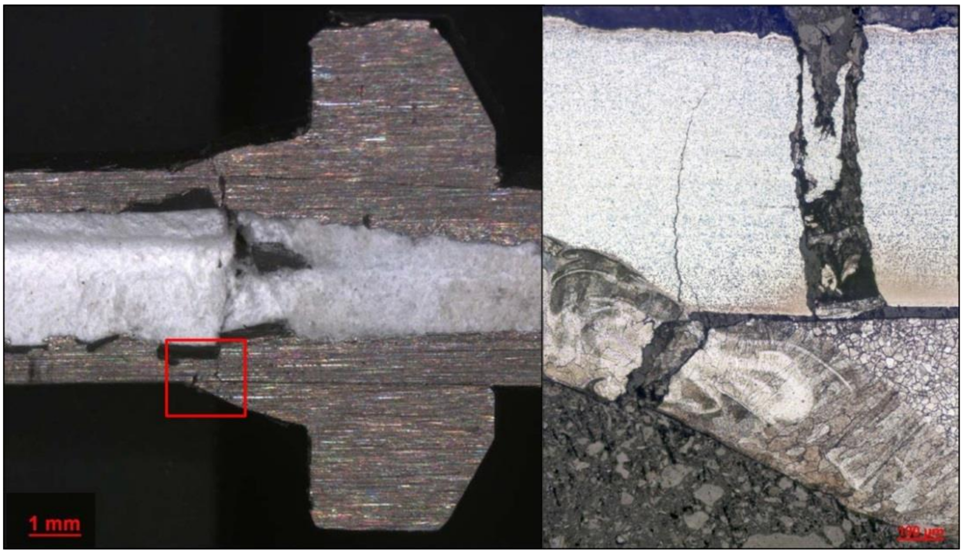

Figure 5.4: Light-microscope image of an sensor (type A) with longitudinal section in the mounting area [6] right – enlargement of the marked area in left picture

Another application for light microscopy is the investigation of the thermocouple wires. Due to the high visual resolution of this method, obtained by consideration of the sectional images of the thermocouple wires, a statement can be made about the grain size and thus a possible recrystallization can be detected. The response to an inordinate respectively excessive temperature would be determined. Also the depth of penetration respectively progress of chemical reactions at the outside of the thermocouple wires may be detected. However, the occurrence of these two effects could not detected after a test period of about 20 h, despite a drilling of the thermowell tip for a direct exposure to air.

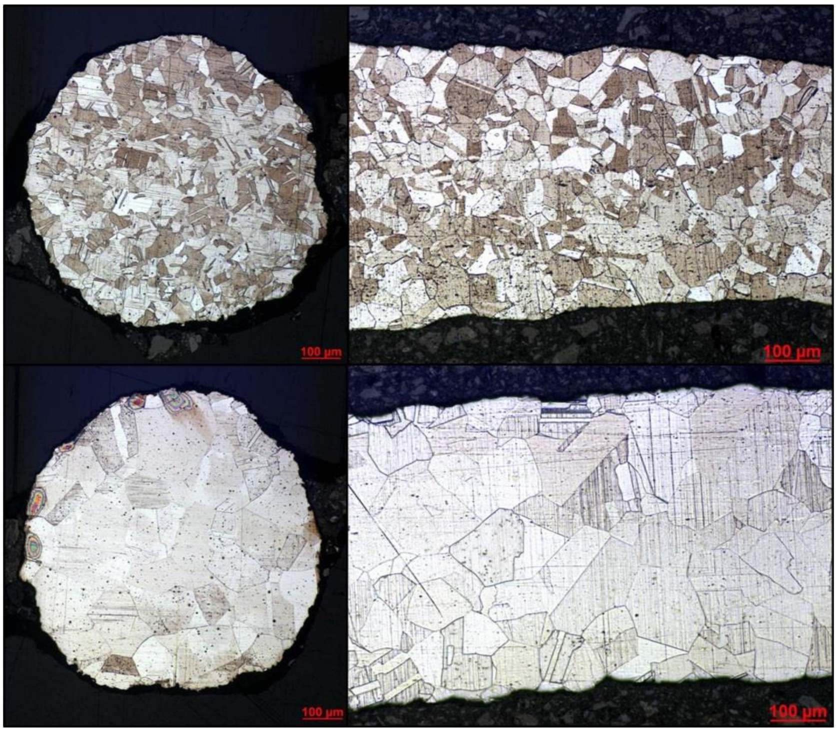

Figure 5.5: Light-microscope image of thermocouple wires with longitudinal and circular section [6] (top- NiCrSi; bottom- NiSi)

6. CONCLUSION

By using a shaker to simulate exhaust gas pulsations, a test rig has been developed which makes it possible to investigate the consequence of thermowell deflections. This allows comparing different design variants. The principle of deformation initiation into the thermowell tip might not being used exclusively in the context of high temperature thermocouples, it could also be applied to the thermowells of all sensors in the exhaust manifold.

To determine which loads are exist in the exhaust manifold, various preliminary examination were carried out, whereby it was possible, inter alia, to determine a frequency and amplitude response at exhaust gas incident flow. Using laser triangulation at different constant engine speeds make it possible to derived a formula, which includes the oscillation frequency depending on pulses per crankshaft rotation. Moreover, it was found that the vibration behavior of the sensor corresponds to a continuous sine wave, which can be implemented on the test rig. Based on increase parameters of frequency, vibration amplitude or temperature it succeed to generate various failure symptoms, which could be breakages in the thermowell or deep body sheet such as thermal wire breakages. By parameter increasing the failures does not have to occur by conventional load in the vehicle, but it is achieved an effective reduction of the testing time to an acceptable level. With this failure symptoms, design improvements of the thermowell could be created, which could be after their implementation in a new sensor,

checked out on their functioning at the same parameters. By increasing the resistance in the test rig can be concluded that a reduction of the error rate in real use is brought about. Testing at normal parameters offers the potential of testing the lifetime probability, but without the inclusion of effects by resonance frequency, since they are excluded by the type of clamping the sensor tip.
Additional sensor investigations with computer tomography and light microscopy allow, among other things, to place an exact verification of breakage propagation. In summary, a test method for identifying error-prone design details and verification of improvements has been achieved.
As a consequence new sensors with reduced effective attack surface for the exhaust pulsation have been developed. These show a clear reduction respectively elimination of failure symptoms as compared to previous generation, while extending the oscillatory length of the thermowell and its stabilization by a body sheet.

REFERENCES

[1] Mladenov, Nikolay: Modellierung von Autoabgaskatalysatoren; KIT Scientific Publishing; Karlsruhe 2010

[2] V. Simon, G. Oberholz, M. Mayer: Abgastemperatur 1050°C: Eine konstruktive Herausforderung, Borg Warner Turbo Systems

[3] Basshuysen, Richard, Schäfer, Fred (Hrsg.): Handbuch Verbrennungsmotor: Grundlagen, Komponenten, Systeme, Perspektiven; dritte Auflage; Vieweg; Wiesbaden 2005

[4] Montenegro, G., Onorati, A., Piscaglia, F., and D'Errico, G., "Integrated 1D-MultiD Fluid Dynamic Models for the Simulation of I.C.E. Intake and Exhaust Systems," SAE Technical Paper 2007-01-0495, 2007, doi:10.4271/2007-01-0495

[5] Köhler, Eduard; Flierl, Rudolf: Verbrennungsmotoren: Motormechanik, Berechnung und Auslegung des Hubkolbenmotors; vierte Auflage; Vieweg; Wiesbaden 2006

[6] University of Applied Sciences Jena / SciTec

Acknowledgment

Research was conducted within the scope of the project "THERMULAB- Thermodynamic multi sensor for monitoring high-temperature processes, especially in exhaust gas ducts". This work was being funded by the European Regional Development Fund and the national funding of the federal state of Thuringia.
We would like to thank the colleagues of the involved companies and research institutions like: tmg GmbH Geraberg, University of Applied Sciences Jena / SciTec, TESONA GmbH&Co. KG, IMMS gGmbH, as well as the involved colleague at the Technical University of Ilmenau, especially Dipl. Ing. Kristian Höpping.

CONTACTS

M.Sc. Axel Wodtke axel.wodtke@tu-ilmenau.de
Univ.-Prof. Dr.-Ing. Klaus Augsburg klaus.augsburg@tu-ilmenau.de