CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 266

Virtual model for continuous turbocharger optimization and monitoring

Digitalizatiion, Connectivity, Artificial Intelligence & Cyber Security

Andreas Hablizel, AVAT Automation GmbH

Matthias Roosz, AVAT Automation GmbH
Clemens Mollik, AVAT Automation GmbH
Dr. Silvio Risse, Kompressorenbau Bannewitz GmbH
Pascal Bauerfeind, Kompressorenbau Bannewitz GmbH
Stephan Wetter, Kompressorenbau Bannewitz GmbH

This paper has been presented and published at the 31st CIMAC World Congress 2025 in Zürich, Switzerland. The CIMAC Congress is held every three years, each time in a different member country. The Congress program centres around the presentation of Technical Papers on engine research and development, application engineering on the original equipment side and engine operation and maintenance on the end-user side. The themes of the 2025 event included Digitalization & Connectivity for different applications, System Integration & Hybridization, Electrification & Fuel Cells Development, Emission Reduction Technologies, Conventional and New Fuels, Dual Fuel Engines, Lubricants, Product Development of Gas and Diesel Engines, Components & Tribology, Turbochargers, Controls & Automation, Engine Thermondynamis, Simulation Technologies as well as Basic Research & Advanced Engineering. The copyright of this paper is with CIMAC. For further information please visit https://www.cimac.com.

ABSTRACT

Exhaust turbochargers significantly contribute to the performance and efficiency of internal combustion engines used in ships or stationary power plants for energy supply. Continuous monitoring of this key component ensures optimal operation and reliability of the entire system comprising the combustion engine and the turbocharger.

Typical measurements such as turbocharger speed, temperatures, and pressures are recorded and digitized for this purpose. Simultaneously, signals from structure-borne sound sensors, which measure vibrations and noises on the turbocharger, are captured to enable correlations between the behavior of the turbocharger and the measured values.

As a result, investigations conducted on turbocharger and engine test rigs have yielded insights into the engine's influence on the vibration signal. Additionally, studies were conducted on irregular conditions replicated on the turbocharger test bench to determine their impact on the structure-borne noise signal. These frequency patterns contain important information and exhibit characteristic harmonic components influenced by the turbocharger speed.

By combining classical measurements with acoustic frequency patterns, algorithms in a virtual model can calculate new parameters. The integration of structure-borne sound, temperature, and pressure data enables real-time optimization of operation and monitoring, as well as providing statistical information over extended periods. Additional parameters are generated by linking virtual sensors, based on mathematical or physical models, with the physical sensors and operation modes.

The determined data and parameters of the exhaust turbocharger are accessible via a standardized interface and can be used, for instance, to optimize the operating point in the engine control system or for evaluation in a higher-level system. This interface allows full integration of the exhaust turbocharger into the engine control system.

From the resulting datasets, meaningful key performance indicators (KPIs) were derived, providing valuable insights into the condition of the turbocharger. The KPIs provide information on the operating point and potential damage patterns. They reveal the need for operation optimization or maintenance requirements. Long-term data enable the detection of changes in operation and performance through time-based comparisons.

With an increasing amount of data, the evaluation algorithms for damage detection in the virtual model of the exhaust turbocharger can be expanded and refined. Consequently, new concepts for the service and maintenance requirements of the turbocharger can be developed.

1 INTRODUCTION

The interaction between turbochargers and combustion engines will remain a key factor for performance and efficiency in civil shipping and stationary power generation systems in the future. Current challenges for turbocharged combustion engines include the versatility of different fuels and the constantly increasing air requirements of the engines.

The introduction of alternative fuels changes the combustion parameters and thus influences the primary energy input into the turbine. Irrespective of the air volumes determined by emission specifications, the increase in performance that has been ongoing for years is leading to a continuous rise in air demand. These developments and the increasing requirements with regard to alternative fuels pose new challenges for the development, operation and maintenance of turbochargers.

Digitalization offers a key strategy for overcoming these challenges by processing measured values. These processed values and key performance indicators (KPIs) help to identify bottlenecks which in turn allow for optimized operation. As part of a joint development cooperation, AVAT Automation GmbH, Tübingen – a provider of control solutions for large engines – and KBB GmbH, Bannewitz – a manufacturer of turbochargers for large engines – are working on the digitalization of turbochargers.

In this presentation, the focus will be on optimizing the operation of turbochargers. In addition, an outlook on future maintenance concepts will be given.

2 MOTIVATION USING DIGITALIZATION

An economic solution to the continuously increasing demand for air, as described in detail in [1], requires new approaches to finding solutions. Digitalization opens up innovative possibilities for the further development and optimization of turbochargers with regard to their development and operation.

A central element of digitalization is operational optimization. By systematically analyzing the function of the turbocharger, the interaction of its components and the predictable behavior in conjunction with relevant input and output variables, models are created that describe the operating state and functionality of the turbocharger.

These models define the requirements for the necessary measuring points in order to provide the required data. The models can be used to derive features that describe the condition of the turbocharger. These features serve as key indicators for the operation of the turbocharger and as a basis for creating availability forecasts. The ability to continuously monitor the turbocharger creates a basis for condition-based maintenance.

The wear of a turbocharger depends largely on the load ramps and operation points. As previously mentioned, both increased performance and stricter emission regulations contribute to a sustained increase in air demand.

However, there are optimum operating points (so-called “sweet spots”) on the turbocharger characteristic curve for each required load point. If the turbocharger detects deviations from these optimal operating points (e.g., due to wear, contamination, or damage), it can inform the higher-level engine control system and provide optimum target values, such as the turbocharger speed. The engine control system can then use suitable actuators (e.g. SOC, lambda) to make minor adjustments (say < 0.5 °CA and/or 0.02 λ) to engine operation in order to optimize the overall operating state of the system. These changes influence the exhaust gas mass flow that drives the turbine and thus affect the performance and efficiency of the unit.

2.1 Electronic component for digitalization

The foundation for digitization is the K2C-Unit (Knowledge to Care Unit) KC2120 (see Figure 1), which is installed near the turbocharger. It records relevant measurement data, processes it using models and calculates features. These features are both stored locally and transmitted as needed.

Additionally, relevant measured values, status information, and parameters can be sent via Ethernet interface to make them available to higher-level systems for further processing.

Figure 1. K2C-Unit KC2120 – robust design for mounting near the turbocharger

The K2C-Unit supports calculations for up to two turbochargers (either for A/B sides or for a two-stage turbocharger) by providing the interfaces for the required sensors.

Figures 2 and 3 illustrate the integration and interfaces of the K2C-Unit within the system:

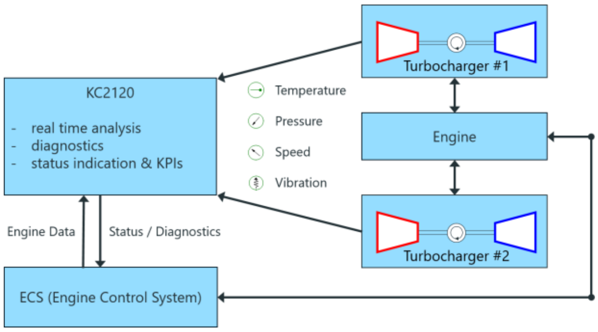

Figure 2. Block diagram of the system.

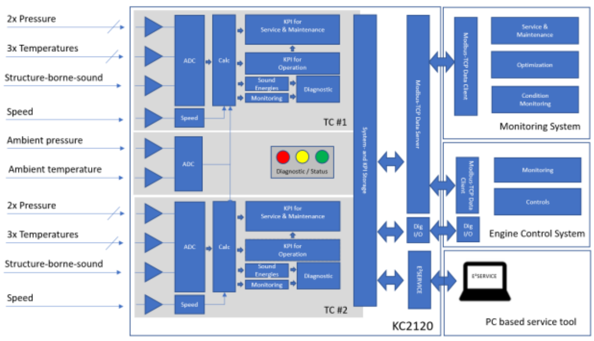

Figure 3. Structure of the KC2120 interfaces.

The large number of generated output variables (features) is provided via the Ethernet interface integrated in the device, which uses a Modbus-TCP interface.

2.2 Benefits of digitalization

Digitalization can not only help in optimizing the turbocharger (TC) operation but also to make the right decisions at different stages of development. The following topics were taken into account:

- Data recording – measurement data can be recorded, KPIs can be generated and stored together with relevant measurement data
- Online analysis – integrated models enable continuous target/actual deviation analysis. In the event of significant deviations, these are communicated to higher-level systems.
- Condition-based maintenance (CBM) – availability models calculate online the time remaining until the next maintenance and inform the higher-level control system.
- Maintenance phase – during maintenance, stored data can be read out to inform maintenance personnel about the condition of the turbocharger and to make the planned measures more efficient.
- Offline data analysis – data recorded by the K2C-Unit in a suitable resolution can be extracted and analyzed during maintenance.
- Further development – practical findings based on the recorded data lead to further development of turbocharger components.

3 MEASUREMENTS

A wide range of different measurement technology is required to implement the functionality of the K2C-Unit.

The input and output behavior of a turbocharger is largely determined by the mass flow rates and the associated changes in enthalpy. Temperatures of the mass flows can be measured using commercially available thermocouples.

The outlet temperature is particularly relevant for the compressor, while temperatures of both the inlet and outlet are of interest for the turbine. The temperature difference across the turbine is a decisive factor in determining its performance.

The mass flows through the compressor and turbine are measured indirectly. Ideally, flow measuring instruments would do this job, but the temperature level, especially the high exhaust gas temperatures, prevents economically viable use.

Instead, pressure sensors are used, which can be used to determine the mass flow rate with sufficient accuracy based on the pressure values and simple calculation formulas.

3.1 Measurement of TC-speed

The decisive variable of a turbocharger is the speed of the common shaft of the turbine and compressor.

This is measured via a cam-like elevation on the shaft. If the cam-like elevation approaches the statically mounted sensor, an AC voltage pulse is generated in the sensor as the cam passes. This pulse is then made available to the K2C-Unit either as a changing analog voltage or as a digital value (0V / 24V).

The types of both cams and sensors are configurable within the K2C-Unit. This enables it to calculate the speed of the turbocharger based on the number of pulses per revolution. Further signals can then be generated from the speed of the turbocharger, such as "TC running" / "TC stopped", or the monitoring of the TC speed to a critical threshold value.

3.2 Structure-borne sound

While capturing of temperature, pressure and speed are established measurements, the use of structure-borne sound sensors enables in-depth diagnosis of the turbocharger and its function.

Structure-borne sound sensors have been used in combustion engines for a long time, particularly for detecting irregular combustion events such as misfiring or knocking. The robust and durable measurement technology ensures reliable protection of the engine. The structure-borne sound provides a wealth of information, the systematic analysis of which enables in-depth insights into the processes within the combustion chambers of each individual cylinder.

As part of a funded project [2] AVAT was able to demonstrate that structure-borne sound sensors can also be used to generate information for the reduction of NOx emissions in combustion engine applications.

Structure-borne sound sensors were also used in preliminary investigations on the turbocharger. It became apparent that the acoustic signal of the turbocharger contains significant frequency components that allow conclusions to be drawn about the operating status of the turbocharger. In combination with the structure-borne sound sensor, the K2C-Unit acts like a stethoscope that continuously monitors the turbocharger.

In turbochargers, the rotational frequency is of particular interest, as it results directly from the turbocharger speed. This frequency is proportional to the load and therefore variable. Further frequencies (harmonics) are proportional to this rotational frequency and also mechanically determined by the number of turbine blades and compressor blades. The weighting of the harmonic components in relation to the rotational frequency provides valuable diagnostic information.

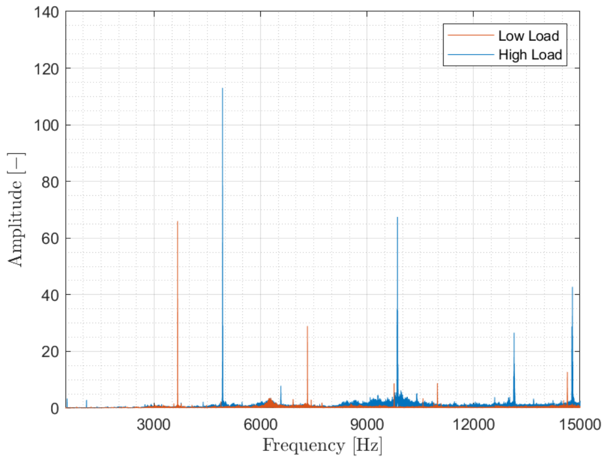

Figure 4. Turbocharger frequency spectra of structure-borne sound – low vs. high load

3.2.1 Frequency information

All frequencies and their different amplitudes form the frequency spectrum. The spectrum changes continuously due to the sound emitted by the turbocharger. To make meaningful diagnostic information available the frequency-related information must therefore be evaluated by the K2C-Unit in real-time.

If the properties of the turbocharger change during operation, e.g. due to contamination, unbalance or similar factors, this can have an effect on the amplitudes of the frequency components. Amplitudes of certain harmonics change or even new frequencies (additional harmonics or periodic signals of a different fundamental frequency) arise that were not previously present.

The way the evaluation of frequencies work can be compared with human hearing. If we know a person’s voice, we can often recognize whether this person is ill (e.g. has a cold) based on changes in their speech melody or tone color. Similarly, changes in the turbocharger components lead to changes in the frequency spectrum. A comparison with reference data makes it possible to detect deviations. These deviations provide valuable information about the condition and function of the turbocharger and its individual components. By continuously monitoring these variables, the turbocharger’s operating condition can be assessed at any time. Based on this monitoring, limit values can be defined and specifically assigned to individual components using expert knowledge.

For reliable limit value monitoring, the sensors need to be suitable to detect differences in the harmonics. Structure-borne sound sensors are ideally suited to detect even subtle changes. Tests on the test bench have shown that off-the-shelf structure-borne sound sensors fitted to the TC can even detect engine-relevant frequencies.

3.2.2 Online frequency-analysis

The example in Figure 5 illustrates that frequency components must always be considered within their specific context. While the rotational frequency of large combustion engines is often static – allowing for frequency analysis to be performed in discrete phases synchronized to the firing order – turbocharger analysis requires continuous monitoring in time domain.

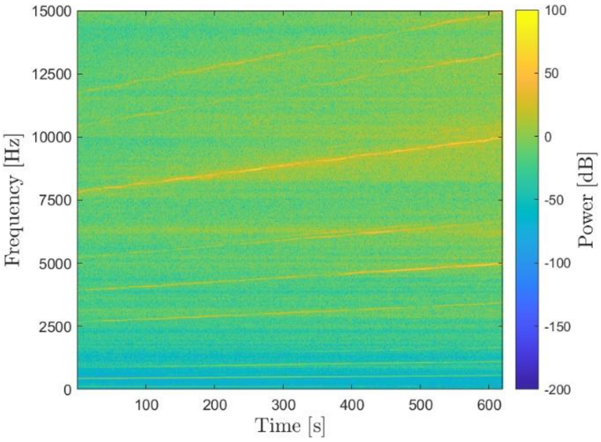

Figure 5. Frequency characteristics during load variation (60-80% load ramp)

The challenge is that the turbocharger speed and thus the rotational frequency is load-dependent, meaning it varies proportionally with the load. The high rotational frequencies and their harmonics make the signal analysis more efficient, as they produce clear, distinct patterns that allow for quick detection of deviations or anomalies.

Specific deviations from typical frequency patterns can reliably indicate phenomena, such as pump surges, and, if operating conditions permit, enable timely countermeasures to be taken.

4 TURBOCHARGER TESTBED

As already mentioned, a series of tests were carried out on KBB's turbocharger test bench, which can help evaluate and develop the new type of analysis.

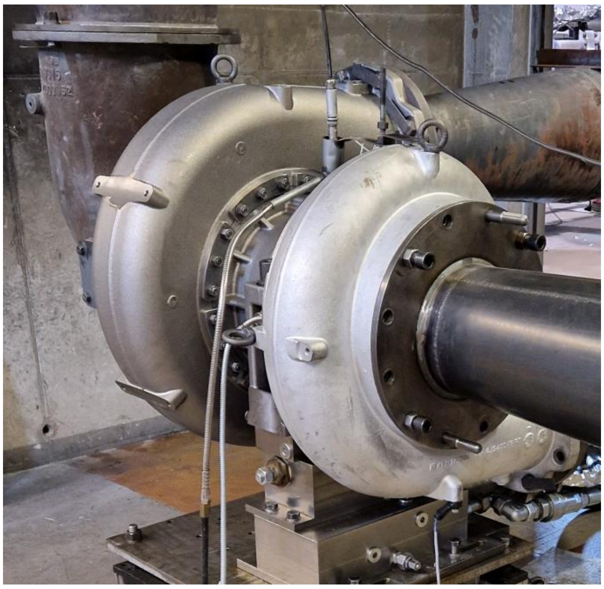

Figure 6. Turbocharger size 6 (HSR6) on testbed

4.1 Description of test bed possibilities

KBB operates multiple test benches designed to accommodate turbochargers of varying sizes. These test benches function in a closed-loop configuration and employ combustion chambers to replicate the exhaust gas flow characteristics of internal combustion engines. Advanced measurement and control systems enable precise adjustment of operating points while capturing detailed performance data of the turbochargers. This facilitates the creation of characteristic maps and provides comprehensive monitoring of turbocharger operating behavior and efficiency.

To enhance the diagnostic capabilities and gain deeper insights into the turbocharger's condition, additional measurement systems have been integrated. These include structure-borne sound measurement technology, which enables the detailed capture of vibration-related data. Structure-borne sound sensors are mounted at optimal locations on the turbocharger to ensure accurate detection of frequency content relevant to operational analysis.

4.2 Typical data of measurements

The structure-borne sound data of turbocharger type ST7-EP recorded at approx. 87% load is depicted in Figure 7:

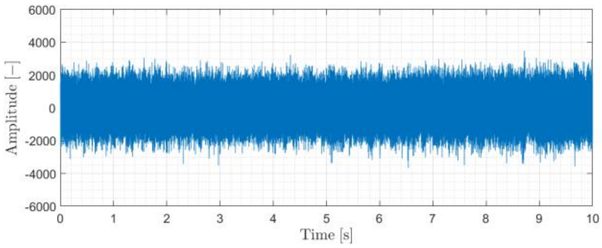

Figure 7. Time series data of structure-borne sound

In the time domain, relevant information is difficult or even impossible to recognize. By transforming the signals into the frequency domain, frequency content that can be assigned to turbocharger components becomes clearly visible:

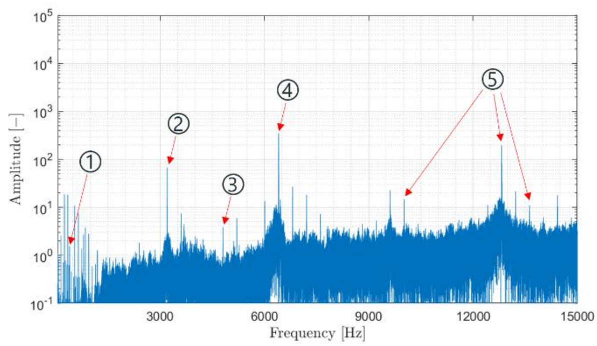

Figure 8. Frequency contents related to turbocharger components

The labeled frequencies in Figure 8 can be clearly attributed to the mechanical and geometrical properties of the TC, making them a primary focus of analysis. Since structure-borne sound is excited by various vibrations and can propagate beyond the immediate vicinity of the source, additional peaks in the spectrum are expected and often originate from the surrounding environment. It is therefore crucial to distinguish relevant signal information from noise.

4.3 Test series

Comprehensive measurement series were conducted on the test bench to collect data using the newly implemented measurement methodology, establishing a reference dataset.

The analysis of this data enables the incorporation of expert knowledge, which is digitized and integrated into the K2C-Unit illustrated in Figure 1.

4.4 Unbalance of rotational parts

One example of irregular turbocharger operation is an unbalance in the system. This unbalance, e.g. due to uneven deposits, increases over time and can be identified using measurement technology.

A balancing quality feature can then be determined. This is based on data from the frequency analysis. If data from a factory-balanced turbocharger is compared to a turbocharger with a balancing problem, the differences can be seen in this diagram:

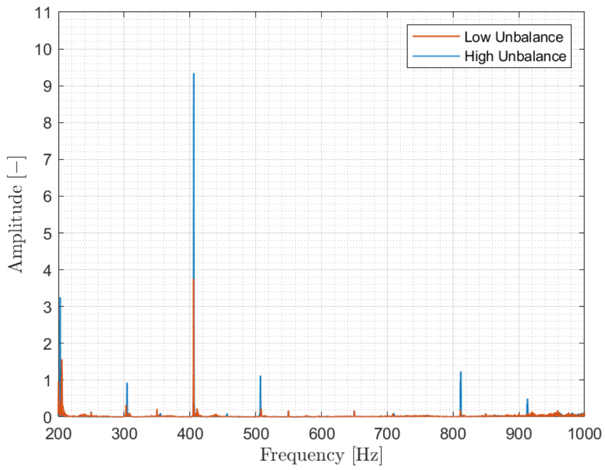

Figure 9. Comparison of frequency spectra for different unbalance conditions during steady-state operation.

This information can be used to deduce the balancing quality from the known values and provide a balancing quality feature based on the permanent measurement across all possible TC speeds.

It should be noted that future operating points (see [1]) on the TC will also further increase the need for early detection of any unbalance.

Other known irregularities can be used to generate further features in a similar way.

5 BUILDING VIRTUAL MODELS

The definition of the features is based on the respective use cases and therefore on the relevant measured variables for calculating the models.

The complexity of the models varies from simple algorithms to models with state mapping of different memory depths. Models can be based on physical relationships (e.g. model for load calculation or for the calculation of virtual measuring points) or be purely motivated by mathematical / phenomenological correlations.

5.1 Model input data

The pool on input data extends from

- Device measurement data
    - Temperatures
    - Pressures
    - Speed measurement
    - Structure-borne sound
- Data from external systems (such as monitoring and/or engine control systems)

The K2C-Unit already provides the most important input data for creating the models. The interface with monitoring and/or engine control systems represents an extension of the data pool. These systems usually have their own sensors, which are essential for fulfilling their tasks.

This allows for integration of additional data into the system. Using such additional data allows calculating further model input values that are not directly available through measurements (e.g. mixture mass flow, which can be calculated from the intake manifold pressure and engine speed).

5.2 Real-time models

In principle, models can be divided into two types:

- Real-time models
- Long-term models

Long-term models analyze the stress on various components by utilizing measured data, calculated KPIs, and transitional information derived from this data. These models enable predictions of component availability based on current and projected operational conditions.

Real-time models, on the other hand, derive operational features from live measurement data, specifically tailored for immediate use in ongoing operations.

In addition to the already mentioned monitoring of features via thresholds, comparative calculations can also be carried out using models.

In addition to feature monitoring through predefined thresholds, comparative analyses can be performed using model-based calculations. For instance, the turbocharger load can be determined either through characteristic curves/maps that relate to specific input variables or by directly calculating it from the turbocharger’s measured parameters. Discrepancies between these values – particularly when exceeding a predefined tolerance range at a given load point – provide critical diagnostic insights.

The collected data, alongside the monitoring of limit values, serves as fundamental input for the engine control system (ECS), as it reflects both the operating condition of the turbocharger and the engine.

Furthermore, models can be applied to evaluate the dynamic response of the turbocharger during load transitions, offering valuable information about its operational behavior.

The K2C-Unit can distinguish between normal and abnormal operating states, with a specific focus on identifying gradual changes over time. These changes are quantified and represented through appropriate characteristic indicators, providing actionable insights.

Examples of KPIs calculated by these models include:

- Component wear and damage
- Deviation from optimal operating conditions
- Operational risks, such as turbocharger surging

5.3 Operational optimization

In addition to their application in diagnostics, models can also be utilized to optimize the overall performance of the engine-turbocharger unit.

The optimal operation of this system can be highly complex, with the following optimization objectives being noteworthy:

- Efficiency optimization
- Wear reduction optimization
- Minimized emissions optimization
- Load switching optimization

When these optimization strategies are visualized within the turbocharger characteristic map, based on a hypothetical mean operating point, it becomes evident that the directional alignment of the optimization varies depending on the specific objective being pursued.

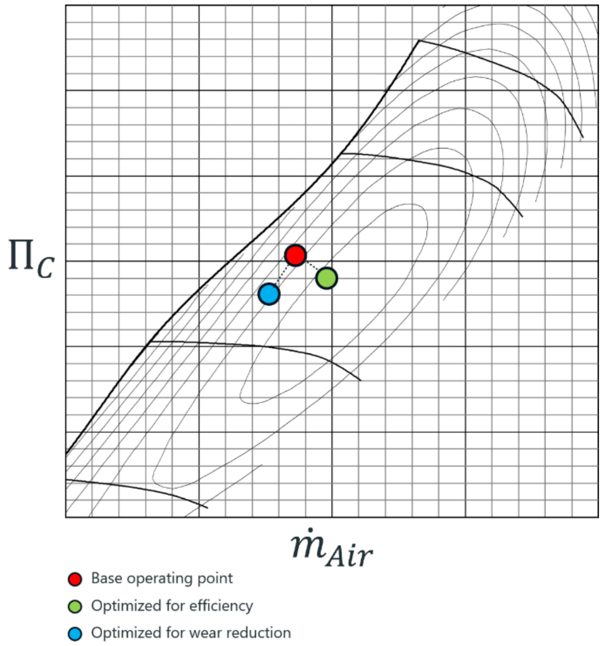

Figure 10. Example of turbocharger optimization for efficiency and wear reduction (pressure ratio vs. air mass flow)

The turbocharger itself is not capable of performing optimizations autonomously; however, the ECS can influence turbocharger operation by adjusting the start of combustion and/or the mixture composition (λ).

Based on the current operating conditions, the K2C-Unit can calculate the optimal turbocharger speed for a given load point. It can provide recommendations to the ECS regarding the target turbocharger speed to be achieved. To ensure these recommendations are actionable, the K2C-Unit must not only suggest the optimal speed but also quantify the benefit of implementing the change relative to the current operational state.

The value of this benefit may vary depending on the optimization objective and the material conditions. For instance, when operating in island mode, maintaining a significant reserve for load dynamics is crucial. Operating near critical boundaries on the turbocharger map increases the significance of the information, which the ECS must factor into its decision-making process.

The ECS determines the priority of specific turbocharger optimizations based on the current operating scenario and the added value of each recommendation. The suggested turbocharger speed is interpreted as a target value, and the ECS implements fine adjustments through modifications to the start of combustion and/or mixture composition, ensuring the target is approached while considering the overall optimization objective and associated benefits.

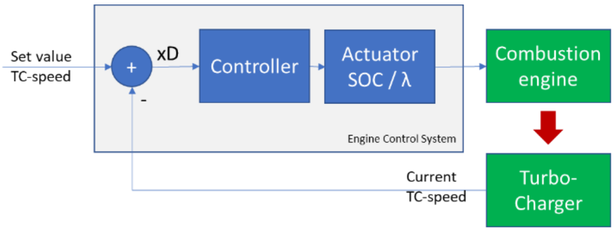

Figure 11. Simplified structure of possible control loop

The relationship between the start of combustion (SOC) and exhaust gas temperature can be quantified as follows: a delay in the SOC by ~0.5° crank angle leads to an increase in exhaust gas temperature of up to 10 K at constant load (unchanged break mean effective pressure (BMEP)). Without compensatory adjustments to emissions, this delay results in a corresponding efficiency loss of 2% relative to the indicated mean effective pressure (IMEP).

Due to the continuous communication between the K2C-Unit and the engine control system, the system can promptly respond to set-point specifications, ensuring optimal engine operation is maintained in real time.

6 NEW WAY FOR A MAXIMUM PERFORMANCE IN OPERATION

6.1 Data acquisition

In summary, the consistent use of conventional and new measurement technology for turbocharger diagnostics opens up new fields in operation and service.

The K2C-Unit functions not only as a computational device but also as a data provider for engine controllers and monitoring systems. Additionally, the integration of supplementary measurement data via Ethernet is supported, such as data locally recorded by other components.

6.2 Data processing

The K2C-Unit processes the acquired data internally using advanced algorithms and modeling techniques. Key performance indicators which reflect the operational status of the turbocharger are computed and made available. The complexity of the implemented models spans from the creation of basic virtual sensors to comparative model-vs-reality analyses and usage-dependent availability calculations.

The insights derived from this processing are utilized to generate optimization proposals for the ECS.

The primary functions of the K2C-Unit can be summarized as follows:

- Acquisition of measurement data
- Continuous monitoring of the turbocharger via integrated measurement systems
- Calculation of turbocharger-specific parameters
- Optimization of turbocharger performance during operation
- Long-term diagnostic analysis of operational data
- Bidirectional exchange of relevant data with the ECS and/or a monitoring system
- Long-term data storage and retention

6.3 Long term monitoring

By using suitable models that are fed with real measured data, measurement data from virtual sensors or other KPls, the K2C-Unit can analyze and represent the condition of the turbocharger and its individual components, including:

- Compressor wheel
- Compressor diffusor
- Turbine wheel
- Turbine nozzle ring
- Turbocharger housing

The detailed status analysis of these components with respect to their operational state enables the system to determine current availability and provide targeted optimization suggestions for operational performance.

This capability also establishes the foundation for condition-based maintenance. The system can detect early indications of required maintenance and deliver precise information on the status of turbocharger components, facilitating proactive and demand-driven maintenance strategies.

6.4 Data Interfaces

Data is the basis for optimization. The optimizations enabled by the integration of measurement technology, turbocharger, and evaluation component are made feasible through the digitalization process outlined in this paper.

The integration of the ECS was also considered opening up possibilities for optimized operation of the combustion engine / turbocharger unit. The optimization proposals, along with the associated value empower the engine control system to enable a new form of operational optimization.

The interface described enables optimization not only at the engine-turbocharger level but also allows higher-level systems to leverage the data for optimizing the entire system, which may comprise multiple interconnected units.

The K2C-Unit functions as a data server, providing measurement data, operational statuses, and calculated features through a standard Modbus-TCP interface. It is capable of simultaneously supplying both the monitoring system and the ECS with real-time data.

6.5 Outlook

The digitalization strategies and possibilities presented here open new pathways for the monitoring and optimization of turbochargers. A central aspect of further development is the verification and validation of the systems, both on the test bench and in real-world operation on customer engines. These tests are crucial to confirm the performance and reliability of the implemented methods.

In 2025, the K2C-Unit will be integrated into the test bench to enable information exchange via Modbus-TCP. This integration will be accompanied by iterative testing to continuously optimize the developed solutions. Subsequently, the field-testing phase on customer engines will begin, during which the systems will be tested and further developed under real operational conditions.

Starting in 2026, the focus will shift to the motor-side integration of ECS and the K2C-Unit, aiming to link condition monitoring and optimization more closely with the engine's control and regulation strategies.

7 CONCLUSION

The integration of the turbocharger with advanced sensor systems and a dedicated evaluation module – the K2C-Unit – establishes a new paradigm in turbocharger monitoring and turbocharger management. This innovation transforms the turbocharger into a fully-fledged mechatronic system and, through the incorporation of sophisticated algorithms and predictive models, elevates it to the level of a "smart turbocharger."

These enhancements enable continuous status monitoring of the turbocharger, providing actionable insights to higher-level systems such as the ECS.

For end users, this results in an increase in availability, as deviations from normal operation can be detected at an early stage, facilitating prompt corrective measures.

Leveraging an in-depth understanding of turbocharger behavior, optimization recommendations can be generated for the ECS, enabling real-time adjustments to enhance overall engine performance (refer to [3])

The K2C-Unit also accounts for long-term operational data, analyzing historical usage patterns of the turbocharger. This analysis enables the generation of actionable recommendations.

The embedded memory within the unit serves as a repository for operational data, providing a foundational resource for refining both the turbocharger's design and the associated evaluation algorithms.

Maintenance personnel can access this stored data through the K2C-Unit user interface, streamlining diagnostics and maintenance workflows. The comprehensive data log captures every operational state of the turbocharger within maintenance intervals, facilitating retrospective analyses. These insights are instrumental in driving continuous innovation and enhancing future turbocharger technologies.

8 DEFINITIONS

CBM Condition-based maintenance

ECS Engine control system

K2C Knowledge to Care

KBB Kompressorenbau Bannewitz GmbH

KPI Key Performance Indicators

SOC Start of combustion

TC Turbocharger

TCP Transmission control protocol

9 REFERENCES AND BIBLIOGRAPHY

[1] Risse, S. 2019. KBB's New Single-Stage Turbocharger Series for Highest Pressure Ratio Requirements, *Proceedings of CIMAC Congress, Vancouver*, Canada, Paper No. 280

[2] Wesche C., Bernhardt. S, Schwarz T., Schmid K. 2019 Cylinder-individual exhaust gas emission estimation of a natural gas engine using structureborne sound signals, *Proceedings of 11th Dessau Gas Engine Conference*, Dessau-Roßlau, Germany, 2019 session 6, pages 290..303

[3] Risse, S., Buchmann K., 2018, Einstufige Abgasturboaufladung für höchste Druckverhältnisse Herausforderungen und Lösungen, *5. Rostocker Großmotorentagung, Rostock*, Germany