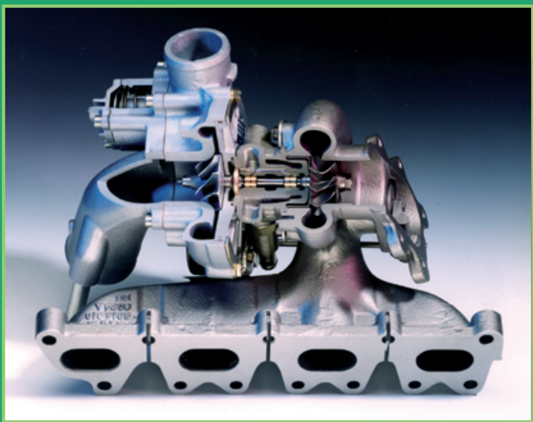
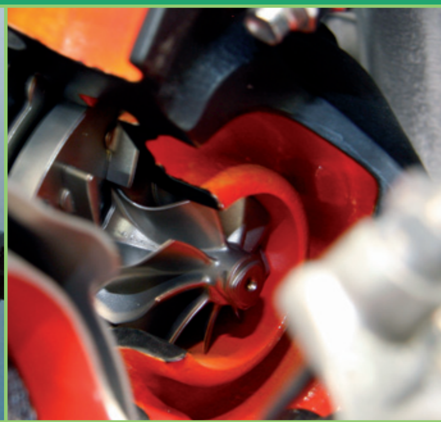
turbo CONTROL

Produktion - *Production*

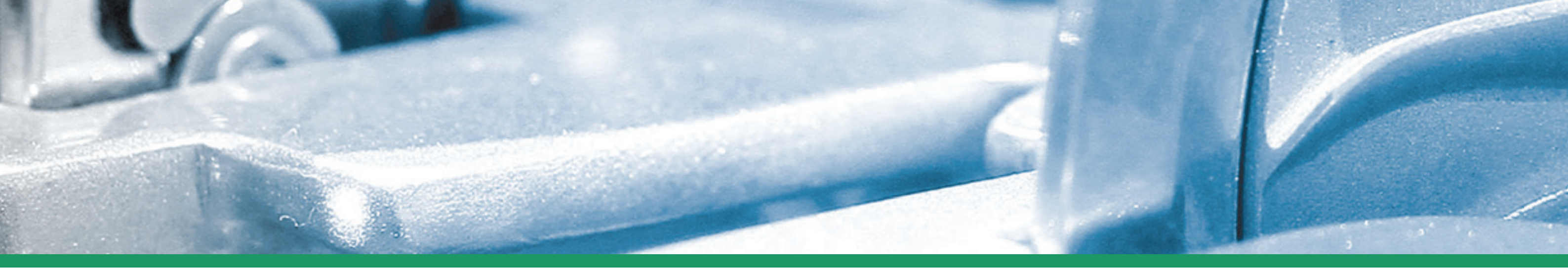




Dynamische zwei Ebenen Wuchtung von Turboladern

Dynamic two dimensional balancing of turbochargers

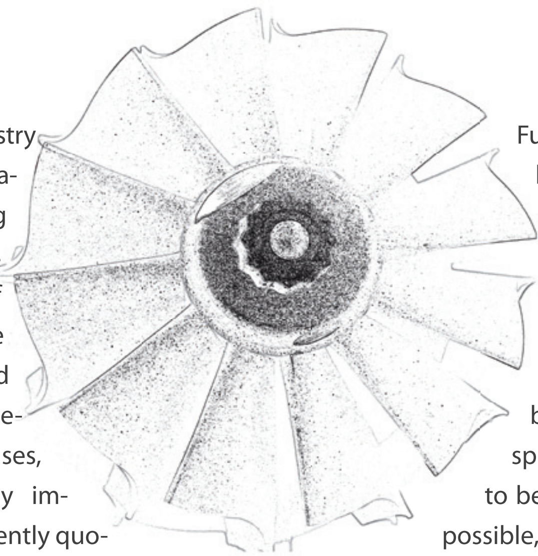
REILHOFER KG
analyse the powertrain - increase the quality



Content of the brochure

The Turbocharger	page	4
The Turbocharger "Core Assembly" – the true "Heart of the Turbocharger"	page	6
The Core Assembly	page	7
Determination of unbalance	page	7
Compensation of unbalance	page	9
Archiving of results	page	10
User interface (UI)	page	11
User access control	page	11
Capability approval	page	12
FAQs – frequently asked questions	page	13
Technical specification	page	16
Images turbo-CONTROL	page	17
References Overview	page	18

The Turbocharger



Traditionally, the automotive industry stands for highest levels of innovation. One of the most demanding areas of powertrain development is optimisation of energy efficiency of modern combustion engines. Due to market globalisation, restricted fossil fuels and ongoing climate debates concerning greenhouse gases, this topic is gaining increasingly importance. "Downsizing" is the frequently quoted buzzword to achieve that objective.

Along with other domains of development like, e.g. electrification, hybridisation, recuperation, automatic start-stop control and injection system, the use of innovative turbocharger with considerably smaller combustion engines is one of the most efficient ways to meet those targets. Main advantages are the reversal of the charge exchange loop of the Carnot process and the decoupling of peak power from the available combustion chamber volume. All in all, this leads to increased efficiency and smaller, lighter aggregates. The output power depends only on the filling degree of the combustion chambers with oxygen (boost pressure) and is largely scalable. High output power will always require an according fuel quantity, however fantastic consumption benefits are achievable in the part-load range.

It has been the consistent use of exhaust turbochargers some time ago, which enabled the comprehensive competitiveness of diesel engines in the car segment today. Due to systematic further development of this technology throughout the last couple of years, it is recommended now, more than ever, for comprehensive use in petrol engines. Benefits remain the same. Whereas diesel engines feature a comparatively low exhaust gas temperature of approx. 850°C at moderate speed, an exhaust turbocharger for petrol engines must be capable of withstanding more than 1000°C at speeds above 300.000 rpm. In addition, this heavy loading test must meet established live times of the entire engine.

Functional characteristics are another highly relevant challenge of these new high-performance aggregates, as they directly influence customer acceptance. Being rather small, these aggregates must be capable to accelerate high masses adequately fast (turbo lag) and reach an acceptable final speed (maximum power). So they have to be designed as small and lightweight as possible, yet as large and powerful as required. It's self-evident, that this can't be accomplished adequately and satisfactorily without specific, individual adaptation to the respective combustion engine.

Boost pressure and achievable volume flow rate are the two dominating system parameters to meet those requirements. Both parameter values are based on rotor speed (turbine – drive shaft – compressor). Excellent engine response means high demand on dynamics (speed change) and the maximum power requires high speed values of 300.000 rpm and beyond.

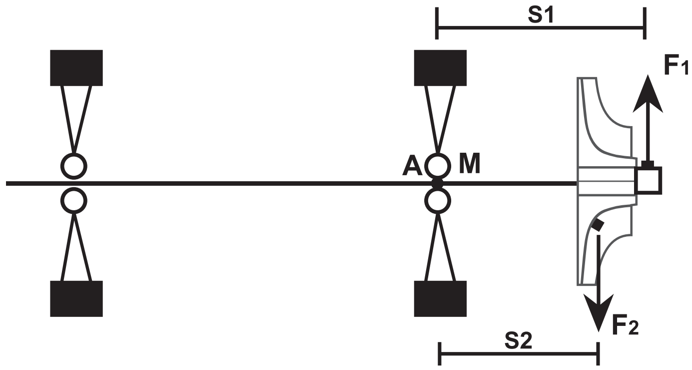
Depending on current operating requirements, a turbocharger runs through an extremely wide frequency range from 0 to more than 5000 Hz. For comparison: a young person's ear can detect a frequency range of up to 20.000 Hz. Even the smallest unbalances of only a couple of milligrammes at system-specific unbalance radii (approx. 3 to 30 mm) not only lead to excessive stress on the used materials, they also generate an often extremely unpleasant airborne and structure-borne noise inside and outside of the vehicle. Whereas other components generate noise of a significant lower frequency rang that adds up to a monotonous noise conglomerate that can be damped, the acoustic spectrum of turbochargers significantly stands out.

To meet the requirements of modern quality standards even in near future, it is mandatory to compensate unbalance throughout the entire operating range.

In the industrial manufatcure of rotors, unbalance is primarily caused by material inhomogeneities and manufacture- and assembly-related tolerances. An unbalance is by definition a radial shift of the centre of mass from the rotational axis of a rotational solid. A rotor is balanced, when its mass centroid axis coincides with its rotational axis, which is given by bearings. A perfectly balanced rotor doesn't transmit any centripetal force to its bearings and thus creates only very small amounts of rotation-frequency related vibrations.

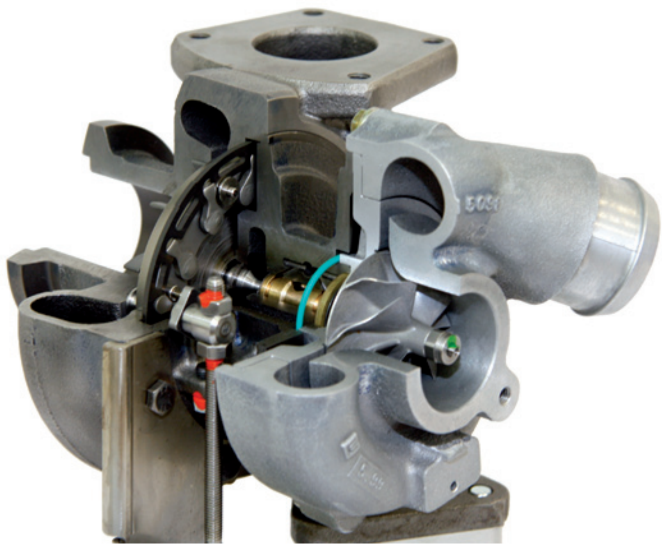
Theoretically, a mounted turbocharger has an arbitrary number of unbalance vectors distributed over the rotational axis. According to the fundamental theorem of balancing technology for rigid rotors, all unbalances of a rotor can always be summarised in two complementary unbalance vectors in two arbitrary radial planes. Under special conditions, even one resultant unbalance vector is sufficient.
This, however, is just a simplified model. In practice, the rotor is showing an elastic behavior and thus a sweep through the entire speed range will show several system inherent modes (natural resonance ranges). So vibration modes not only show a radial deflection of the shaft from its bearing-defined rotational axis (so called static unbalance), but also different bending shapes of the rotor (dynamic unbalance). Static unbalance can be adequately characterised and balanced by a single vector. The differently natured tumbling motion of dynamic unbalances, however, can only be balanced by targeted application of counter-torque (e.g. at least two balancing vectors) on the shaft.

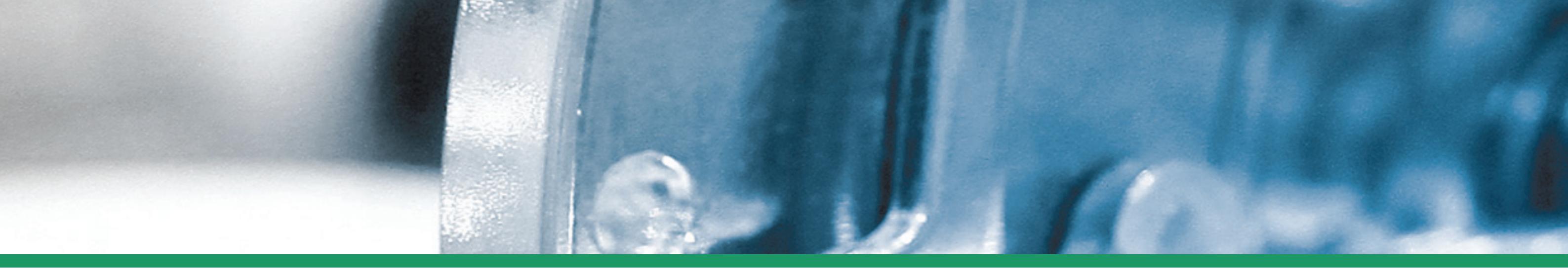
In every operating range the unbalance vectors pose different impacts on the shaft motion and mutually influence each other. To sufficiently stabilise the shaft motion in every operating sub range, only an optimised compromise can be found.
To put it short: the objective is to reduce rotationally symmetric vibration amplitudes for each speed or mode range. It should be accepted, that the theoretical optimum for one range possibly has to be compromised in favour of another range.



2-Plane unbalance on turbochargers

According to the state-of-the-art, turbocharger core assemblies (bearing housing incl. assembled rotor, excl. compressor and turbine housing) are dynamically balanced to operating conditions in two planes on the compressor side. Due to construction constraints, this is done by targeted material removal at the shaft tip and between the blades of the compressor wheel. In theory, an additional corresponding balancing material removal at the turbine side would be required. Practically, also due to construction, this side is the significantly stiffer and higher-mass part of the rotor. As it is subject to almost equal production tolerances, it shows quite similar amounts of unbalance. The counteractive mass inertia normally compensates vibration amplitudes to an extent, that the theoretically required (but procedural much complexer) balancing in four planes becomes economically unattractive.





As early as 1995, KKK (later acquired by BorgWarner) requested REILHOFER, to measure the unbalance of turbochargers using the REILHOFER delta-ANALYSER system. For that purpose, the specialised turbo-CONTROL system has been developed. The globally first diagnosis- and 2-plane-balancing-system was born, which made the measurement during the fast ramp-up and provided balance correction data in two planes.

Since that time, the system has been continually developed further, so that today it is capable of running a multi channel, multi vibration direction parallel acoustic spectral analysis in form of an online order analysis. The main focus of attention during development has been and still is quality of analysis (measuring technology) and highest possible degree of automation (analysis software). While in its early days the system had to be manually calibrated and configured, to define the relation between unbalance and measuring amplitude, this process now runs fully automated. As soon as the process has been mechanically installed and some geometric parameters for material removal have been configured, the system autonomously learns, which plane(s) to choose for balancing, to reach the required limit values, if possible. A major challenge was the permanent minimisation of gap dimensions and related tolerance limits due to increased demands on efficiency levels. Test damages may occur due to possible vibration deflections of the rotor (condition as delivered), when driven to nominal speed. The rotor must not be driven to nominal speed, before a sufficient vibrational quality level has been demonstrated at a lower, defined speed value. This, however, leads to a significant increase in test time, as several balancing cycles are needed. Using statistical evaluations, REILHOFER succeded in reducing this increase in test time to a minimum. So today's quality levels of turbochargers ensure, that balancing processes have no adverse effects on profitability.

The Turbocharger "Core Assembly" – the true "Heart of the Turbocharger"

What is particularly important:

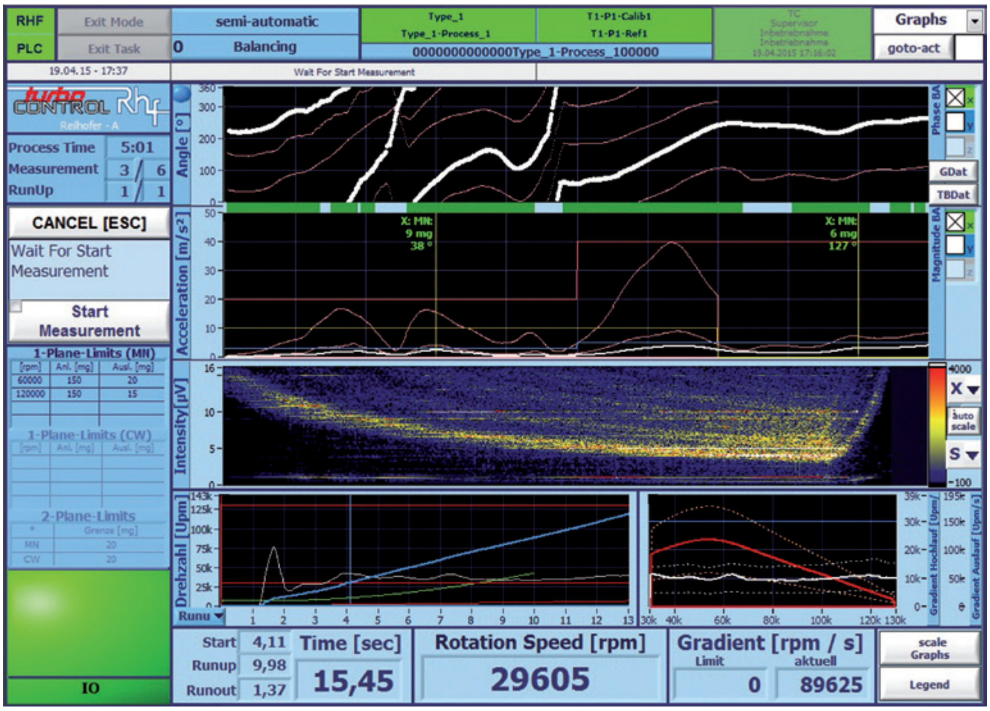
- Removal of unbalance
- Optimisation of dynamic behaviour
- Quality analysis
- Check for acoustical anomalies
- Compliance with given acoustical limit values

Based on turbo-CONTROL, REILHOFER KG provides a longstanding system, which reliably manages all of these challenges.

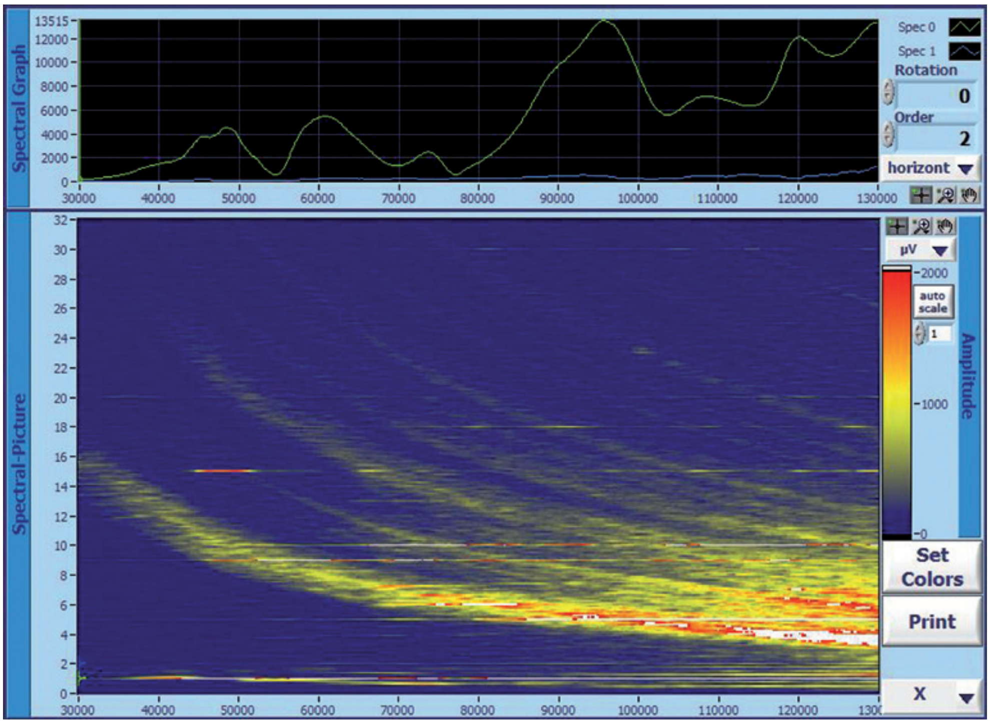
The Core Assembly — Heart of the Turbocharger

... Three Steps to Success

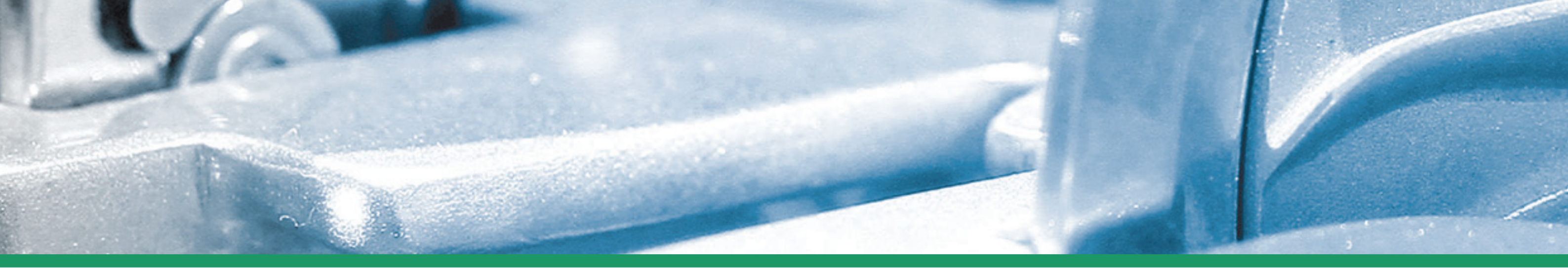
1 - Determination of unbalance

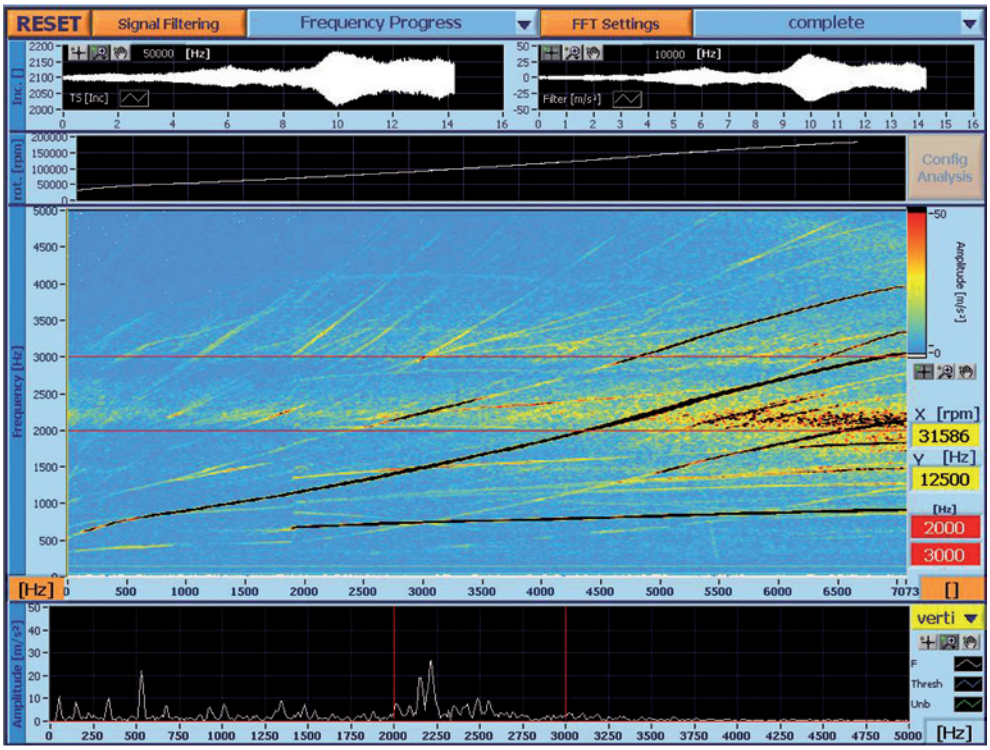


Measurement screen of the ramp with acceleration curve, phase response and pulsations graph



Order analysis to determine unbalance





Frequency analysis to detect non-speed-synchronous effects

Relative determination of unbalance in two planes covering the entire operating range

- Reduction of wobbling
- Reduction of noise emission
- Increase of service life

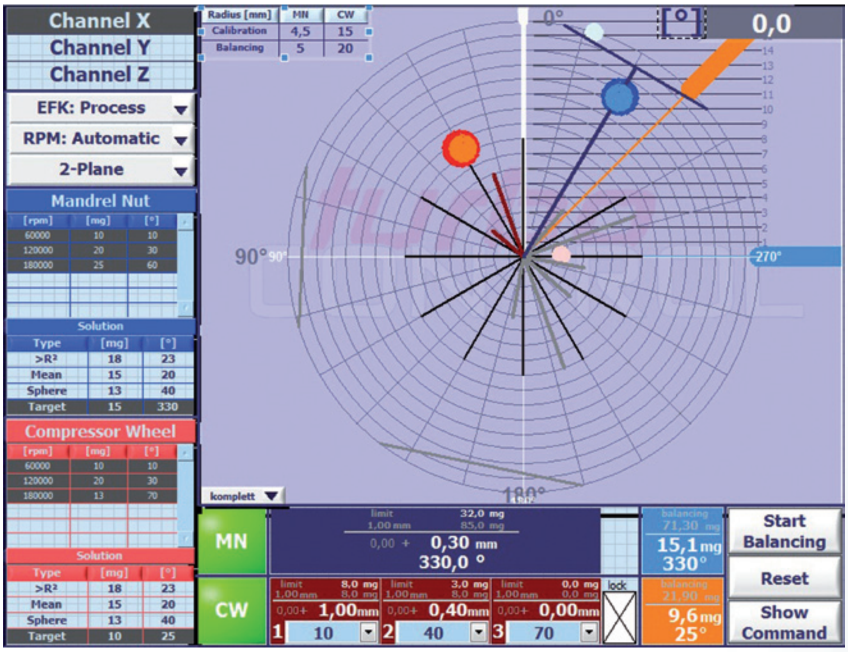
Dynamic measuring during ramp-up

- Dynamic behaviour (monitoring of waveform and speed curves)
- Unbalance resolution < 1 mg per order analysis
- Speed up to 300,000 rpm
- Short testing times < 15 s
- Online limit value monitoring (unbalance and speed curves)
- Predictive pre-balancing at low speed to prevent test damages
- Peak-hold monitoring in the frequency domain

Non-reactive multi-channel measurement value reading

- Acceleration → piezoelectric
- Speed → magnetic
- High reproducibility
- Parallel pulsation measurement
- Additional axes

2 - Compensation of unbalance



Editing screen for a turbocharger

Determination of unbalance vectors

- Selection of balancing speed ranges – manually or fully automated
- Autonomous learning of amount of balancing material removal – no calibration required, but possible
- Classification of core assemblies according to dynamic behaviour for best possible comparability and minimisation of balancing cycles
- Automated decision, which and how many planes to choose for balancing
- Determination of unbalance vectors based on limit value definitions

Calculation of processing instruction

- Arbitrary geometries of turbocharger and tools (shaft nut / compressor wheel)
- Mass distribution
- Overlaps (processing history)
- Processing sequence
- Optimisation regarding limit value definitions and detection of "balancing impossible" conditions

Unbalance compensation – online monitoring

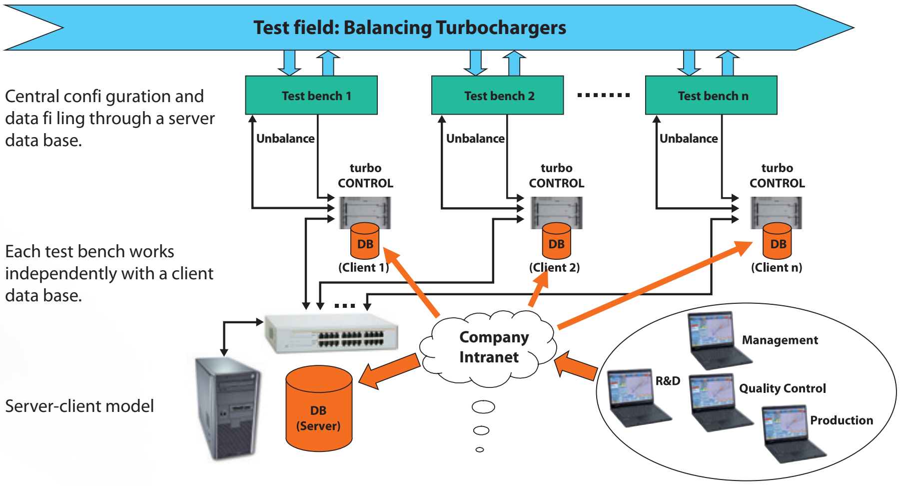
- Angle
- Depth
- Interpretation

Self-learning (statistical)

- Action → reaction
- Tool wear
- Minimum material removal
- Minimum scrap
- Consistent quality
- Optimal throughput through minimum number of balancing cycles

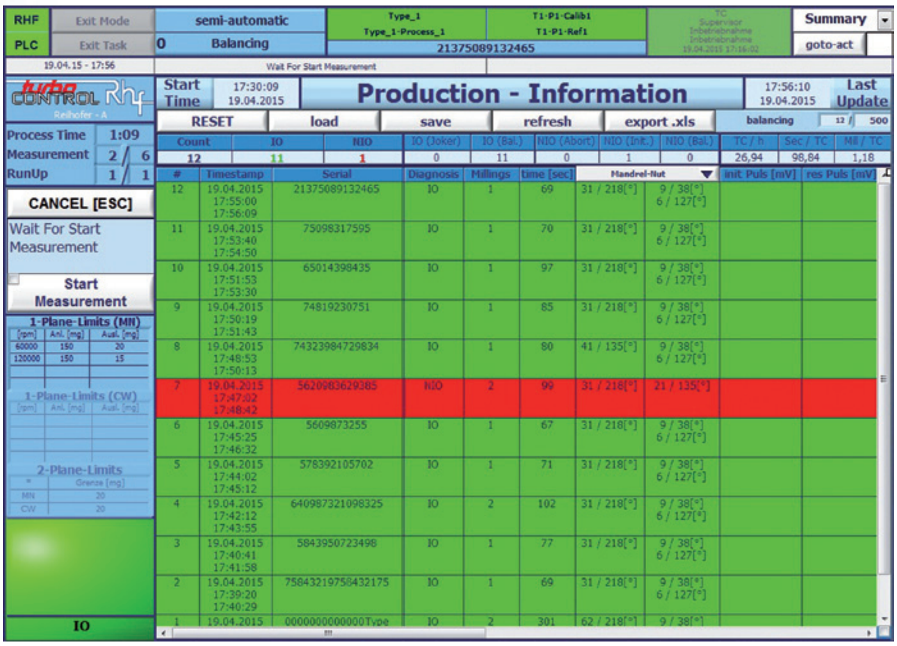
3 - Archiving of results

Standardised database system
- General compatibility (MS SQL)
- Easy, performant accessibility
- Safety and consistency of data



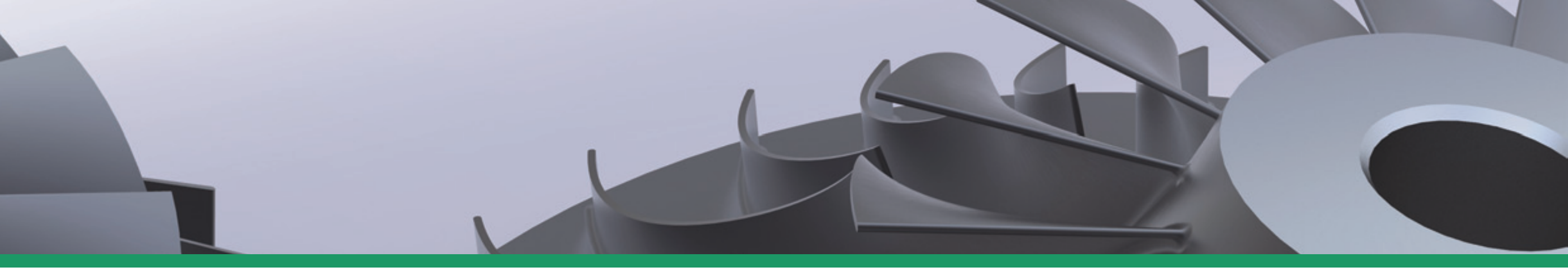
Integration of turbo-CONTROL in the test field

Production history
- Test object specific
- Machine specific
- Turbocharger dynamic initial/residual
- Processing processes



Production database with all information from the turbocharger balancing machine

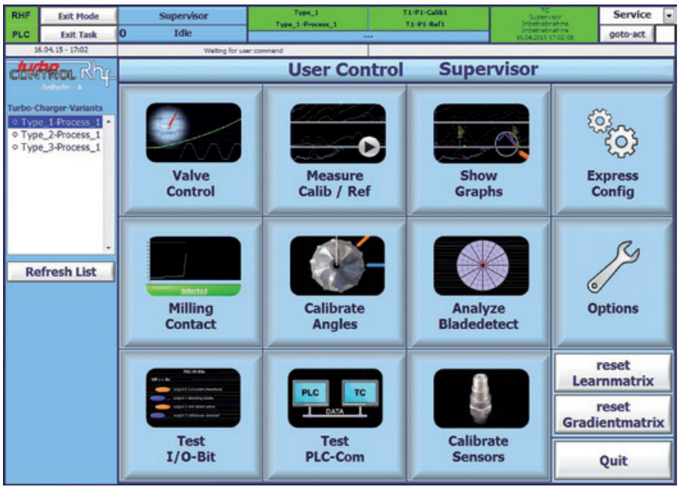
Production monitoring
- Identification of statistical deviations
- Earliest possible intervention/reaction
- Quality assurance
- Quality control loop



User interface (UI)

- Multilingual — straightforward / clearly understandable — informative
- Global remote-access for process monitoring
- Intuitive operation — matched to production environment

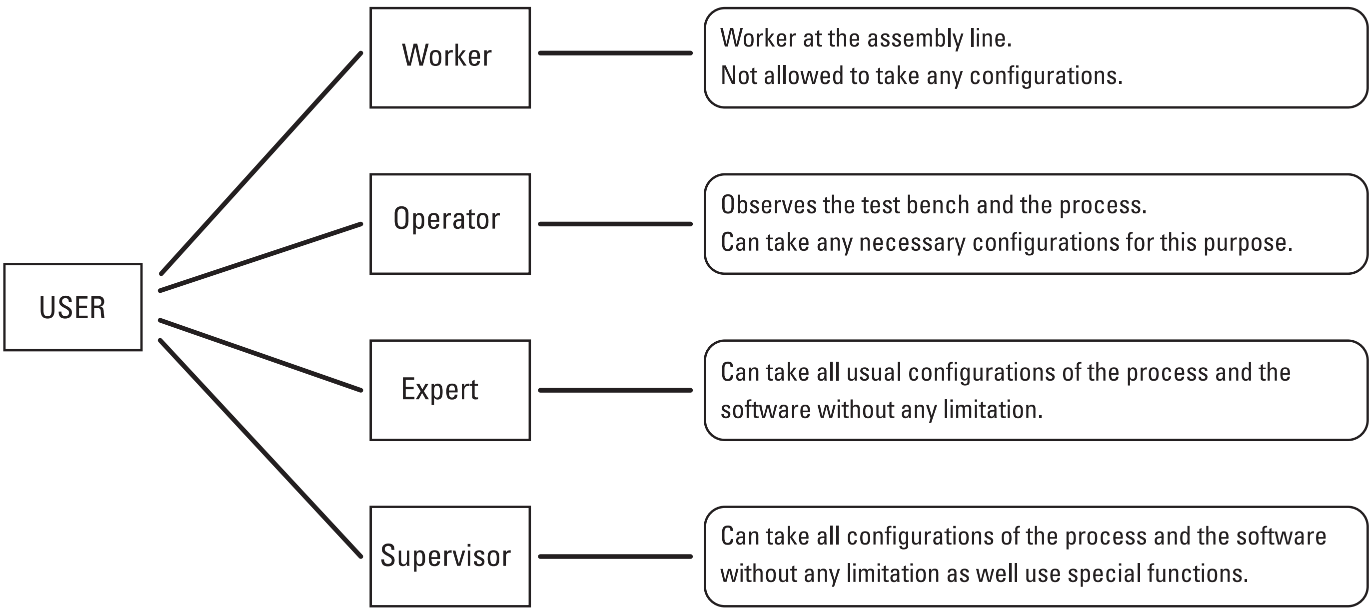
Startup Display



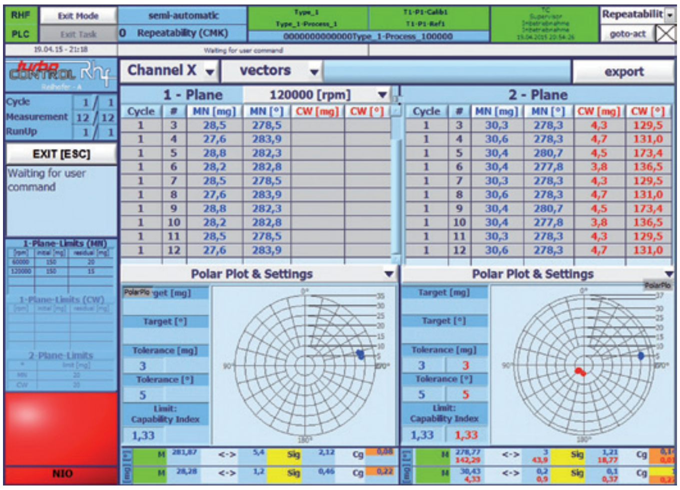
User Control

User access control

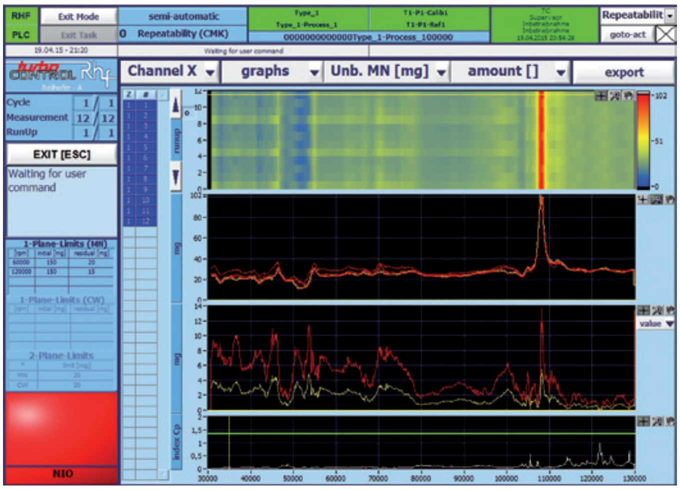
- Production (Worker) – set-up (Fitter/Operator) – configuration (Expert)
- Management (Supervisor)



Capability approval



Reproducibility unbalance results



Reproducibility of measurement results

• Automated – reproducible – logged – c_p, c_{pk}, %GRR

Detailed analysis of measuring values & influencing variables (graphical and scalar)

• Calibration data

• Referencing

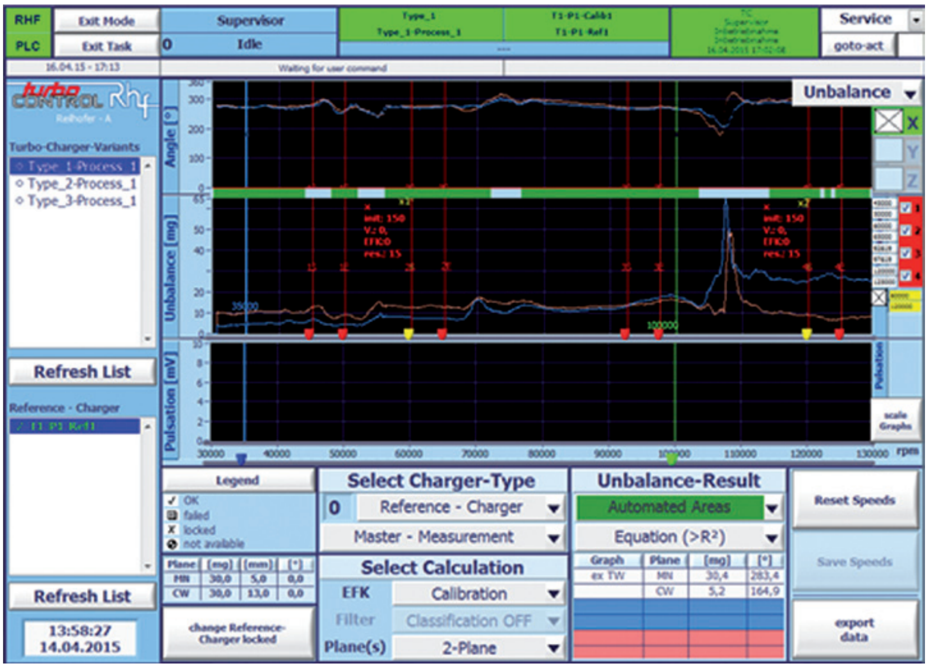
• Influencing factors (correlation between measuring values and balancing material removal)

• Base data: Calibration, production, individual balancings

• Unbalance courses

• Balancing speed ranges (specific speeds, ranges, automated filters)

• Procedure for calculation of unbalance vectors (mean value, statistics, mass centre, target vector)



Visualization and Analysis of calibration data

FAQs – frequently asked questions

What do I need to determine the unbalance of a turbocharger?

To be able to determine the unbalance of a turbocharger, you first have to know, how the rotor develops its vibration characteristics and how they manifest. Regarding highly dynamic heat engines, it is not really expedient, to cover only one selected operating point. In fact, the entire range must be covered, to obtain a meaningful quality assurance – requiring, in addition, the least possible test time. High-precision resolution of magnitude and phase of the speed dependent fundamental vibration as well as high-accuracy in balancing material processing down to the milligramme range are of vital importance. Exactly this objective has been achieved with the latest generation of REILHOFER's turbo-CONTROL. In cooperation with renowned manufacturers of test benches, REILHOFER KG has developed fully automated and manual balancing test benches. After fully automated loading of the machine, compressed air is used to constantly accelerate the core assembly, depending on size, to speed values up to 300.000 rpm and then decelerate it again. Finally the determined unbalance gets compensated. The concept of vibration dynamics of the unit is unparalleled and specifically tailored to requirements. Using REILHOFER's specially developed and optimised process technology for signal acquisition, processing and interpretation, a test cycle time of under two minutes per device has been achieved under optimal conditions.

Can I determine the unbalance in two planes over the entire operating range with only one sensor?

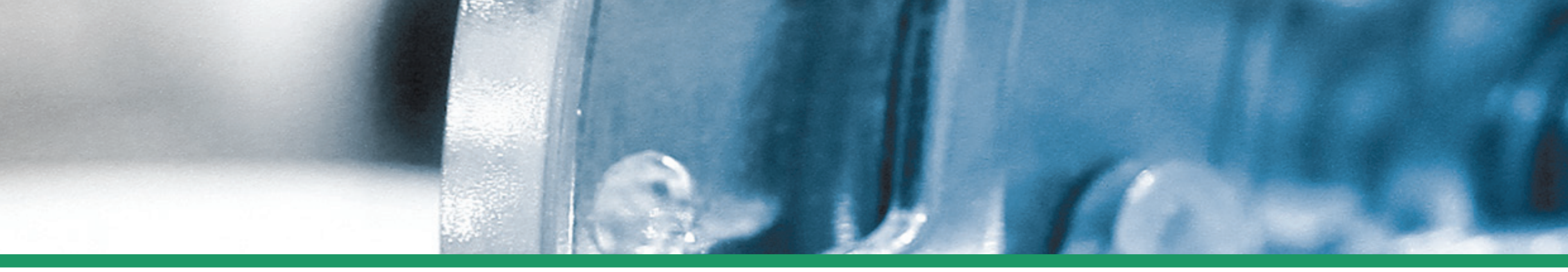
YES. Using REILHOFER's turbo-CONTROL, a rotor's unbalance has been successfully identified in two different radial planes with only one sensor, placed at a suitable position. This has been made possible only through signal acquisition over the entire speed range, a highly complex interaction between optimised test bench dynamics and a special vibration measurement, as well as the unique evaluation method. The test method is based on order analysis: a direct interpretation of vibration signals by means of a high-precision magnetic speed acquisition. The speed sensor is an in-house development of REILHOFER KG.

What is the maximum speed that I can measure?

Currently, the method is limited to a speed value of 300,000 rpm. As the test is exclusively carried out with cold compressed air up to nominal speed, the test object itself is the limiting factor, because the enthalpy of hot exhaust gases at normal operation is not available. Speed values beyond 300.000 rpm would jeopardise the structural integrity of the test objects, so they do not "yet" occur.

How long does it take to determine the unbalance of a turbocharger?

Finally, the turbocharger itself and the test speed to be run determine the possible minimum test time. For example, a test speed of 200.000 rpm and a speed gradient of 30.000 rpm per second results in a ramp-up time of just under seven seconds. The ramp-down phase is also controlled, as a sudden turn off of the compressed air means a thrust reversal and may lead to test damages. So typical test times are in the range of 15 seconds per measurement.



Can I measure and machine different turbocharger geometries?

YES. From a metrological point of view, you can test and balance turbocharger of arbitrary size and geometry with turbo-CONTROL. All required parameters (mass, radius, metrological dynamic range etc.) are controllable via turbo-CONTROL's setup menu. The test bench itself is also scalable to suit almost all imaginable geometries. Due to the fact, that a test bench in a production environment is always associated with costs, key design objectives have been a highly compact foot-print, combined with the highest-possible degree of automation. The current implementation is optimised for the needs and size requirements of the automotive industry. However, dimensions are scalable to virtually any size to also meet the needs of the commercial vehicle sector.

How precise is the unbalance resolution?

From the metrological point of view, a resolution of under 0.1 milligramme and below is no problem. All unbalance masses are calculated with a resolution of 0.1 milligramme at given unbalance radii (for compensation, only the information on masses is of importance; radii only establish the correlation between calibration and balancing operation). The (in practice) achievable accuracy is related to the interaction between individual setup-kit, manufacturing accuracy of the turbocharger and various required operating parameters, like, e.g. oil type, oil temperature, oil pressure, oil flow rate, clamping forces and driving compressed air. During rotor acceleration at room temperature with compressed air, the compressor side is heated up to more than +100°C. The turbine side is cooled down below -40°C. The flow into blades can only be implemented as tangential impulse drive and thus doesn't meet the conditions, for which the turbine has been designed (driving by enthalpy in hot exhaust gases). As opposed to classical balancing technique, measures can't be taken directly in the bearing positions. Only the transfer function (unbalance – rotor – oil film – bearing bushing – oil film – bearing housing – setup-kit – sensor) can be analysed. Taking into account all these influencing variables, an accuracy of approx. 1 mg is achievable in practice.

Are multi-channel measures taken in parallel?

In addition to vibration and unbalance measurements, some more parameters are of interest within the scope of turbocharger test, like, e.g. pulsation in the compressed air and further frequency analyses (peak hold) for non speed synchronous phenomena. From a quality point of view and to safeguard measured signals in production, it may be necessary to acquire additional acceleration signals and directions to make sure, that all potentially present shortcomings are identified. Today, turbo-CONTROL covers four measurement channels concurrently and 100 percent synchronously.

Is the measurement non-reactive and reproducible?

All vibration measurements are based on piezoelectric acceleration sensors from renowned sensor manufacturers. They are directly installed at suitable positions in the test bench. Speed is measured through the magnetised rotor nose via a specially developed speed sensor, which can be arranged axially or radially with regard to the rotor. This arrangement ensures reliable and non-reactive testing of core assemblies. Signal reproducibility is almost independent of sensors. It is primarily defined by the test object as well as the test bench.

Can the entire instruction for balancing be created?

YES. Turbo-CONTROL automatically creates the balancing instruction. It sends it to the test bench, where it is carried out under permanent monitoring. The correction planes are normally located between the blades of the compressor wheel and at the rotor nose (shaft nut). Both vector distribution to up to three milling channels between the blades and the calculation of the material removal at the shaft nut can be purposefully mapped and freely configured. What's more, monitoring of the machining history ensures that permissible milling depths are not exceeded and overlapping millings will not lead to significant miscalculations.

Is the machining process monitored online?

YES. The machining process is double-monitored: by the turbo-CONTROL system and by the test bench control as well. First cut control is also carried out by an acoustical vibration measurement by the turbo-CONTROL system. Only if both systems identify the correct angular position, processing will start. As only those statistical machining processes may be used to optimise compensation instructions that have been declared faultless, monitoring by the turbo-CONTROL system is mandatory. In addition, faulty processing units must be prevented from generating irreparable damages to test object or test bench.

Will the machining process be filed?

YES. Every unique machining step gets stored in a complete machining history in a MS SQL database, including diagnosis data. It is possible, to retrieve data according to customer specific requirements.

What about production fluctuations?

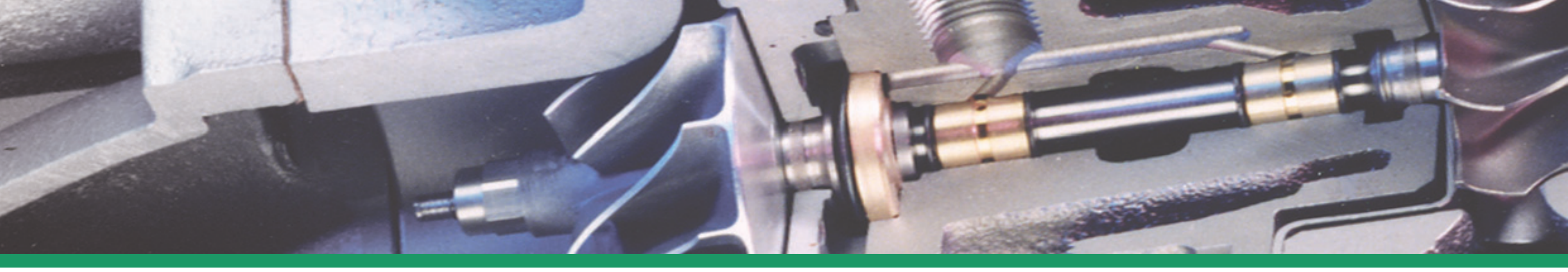
Every measurement run is stored in a MS SQL database. The record includes the complete measured curve of acceleration values in magnitude and angle, plotted versus speed, as well as all freely definable unbalance vectors in one or two planes. The comprehensive base of data permits a large number of statistical analysis methods to be able to detect, e.g. medium- and long-term production fluctuations. For example, continuously increasing acceleration values of the unbalances indicate a drift in manufacture processes within an upstream production step.

Are evaluation options available?

Due to highly-diversified customer requirements, REILHOFER KG offers only a very limited access to result data. Instead, REILHOFER puts great emphasis on standardised interfaces and replication of result data on the customer's network (MES etc.), so a maximum flexibility is given. Consistent use of established data base technologies enables REILHOFER, to offer each customer the access method that optimally suits their needs. Every customer becomes master of its own data. This builds trust and confidence. Secrets stay, where they belong: in the manufacturer's production and not at the supplier's.

Are we the first to use the system?

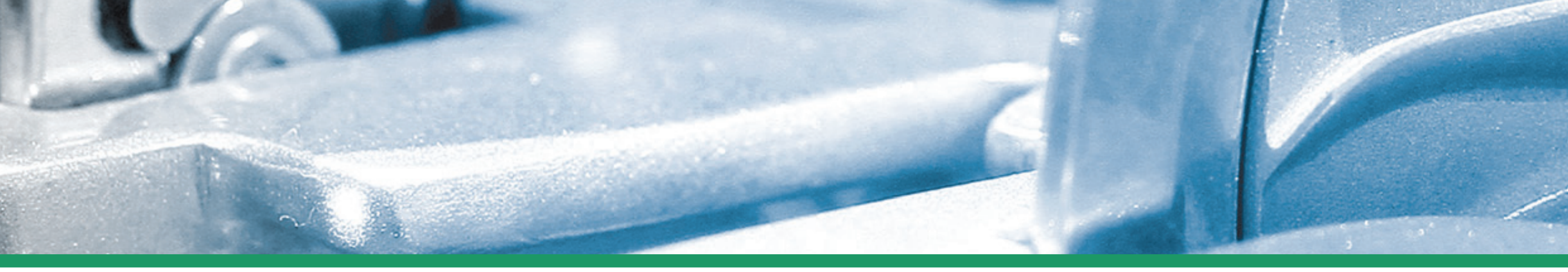
NO. More than two hundred turbo-CONTROL systems are in service worldwide. And more than **150 million** two plane balanced turbochargers speak for themselves and, of course, for us.



Technical specifications turbo-CONTROL

Measuring device:	
Signal inputs:	8 Acceleration Channels (4 parallel) 3 speed channels
Input sensitivity:	±1 mV to ±10 V
Sensor supply:	4 mA constant current
Resolution:	1,25µV
Sampling rate:	Freely programmable; 2.5 Msample/s max.
Speed:	0 to 300,000 rpm
Dimensions:	Rack 483 mm (19 “), 3 U 110/230 V, 50/60 Hz, 350W
Operating temperature:	-10°C to 55°C, IP 30, protection class I
Signals/data processing:	
Frequency & order analysis:	integrated
Data storage:	SQL database, MS SQL Server
Visualisation computer:	
Industrial PC	State-of-the-art, RAID 1 Rack 483 mm (19 “), 4 U 110/230V, 50/60Hz, 350W
Operating system:	Win 7 Ultimate
Communication:	Connection to PST-host, company LAN
Control/Communication:	
Inputs:	20 channels 24 V dc 1 optical encoder
Outputs:	24 channels 24 V dc 1 constant current 4 to 20 mA (for inlet air valve)
Communication:	Profibus DP, Ethernet, serial
Ethernet:	10 / 100 / 1000 Mbit/s
Optional:	Speed sensor

Images turbo-CONTROL



References

DETROIT DIESEL

Bosch Mahle TurboSystems

BorgWarner Turbo & Emissions Systems

IHI CHARGING SYSTEMS INTERNATIONAL

DAIMLER

BorgWarner Turbo & Emissions Systems

湖南天雁机械有限责任公司
HUNAN TYEN MACHINERY CO.,LTD

Kangyue Technology Co. Ltd.

BorgWarner
Turbo & Emissions Systems

VÖFON
Passion and Efficiency

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