How fit is your wind turbine?

Wölfel Offshore Monitoring Approach

Wölfel

Developing people. Engineering the future.

Summary – The Wölfel Monitoring Approach

As a global provider of Structural Health Monitoring (SHM) solutions, Wölfel understands the challenges of creating a valuable product for the long-term observation of Wind Turbine Generators (WTG). We see SHM as a data-driven process capable of providing reliable diagnoses and assessments of the structural performance, and ultimately add value to your assets. Our monitoring approach combines our company's long-term expertise in hardware design and installation, mechanical and structural engineering, data science and software design, to provide a tailored solution able to address any offshore wind park SHM needs such as:

- fulfilment of monitoring requirements by authorities
- reduction of maintenance work and costs
- optimization of the wind park operation
- improve asset management
- enabling lifetime extension and
- continuous validation against design assumptions

The success of an SHM system relies on the optimal planning and execution of a wide spectrum of tasks from choosing the right hardware and sensors, designing software, implementing algorithms, and ultimately proving engineering support to take the right O&M decisions. With a dedicated team of experts in hardware design, software developers, data scientists and structural engineers, Wölfel can support all stages of the SHM process from beginning to end.

After many years of experience, our monitoring approach has identified four monitoring goals which yield the most value to investment ratio in an SHM system for offshore WTG:

Monitoring of ...	**Helps us detect ...**
Loads and lifetime consumption	● problems in operation ● deviations from load assumptions in design ● "black sheep" in your fleet ● critical operational states
Dynamic state	● anomalies in the global behaviour ● scour
Vibrations at tower top	● problems in operation ● critical operational states
Verticality	● ground settlements ● soil degradation

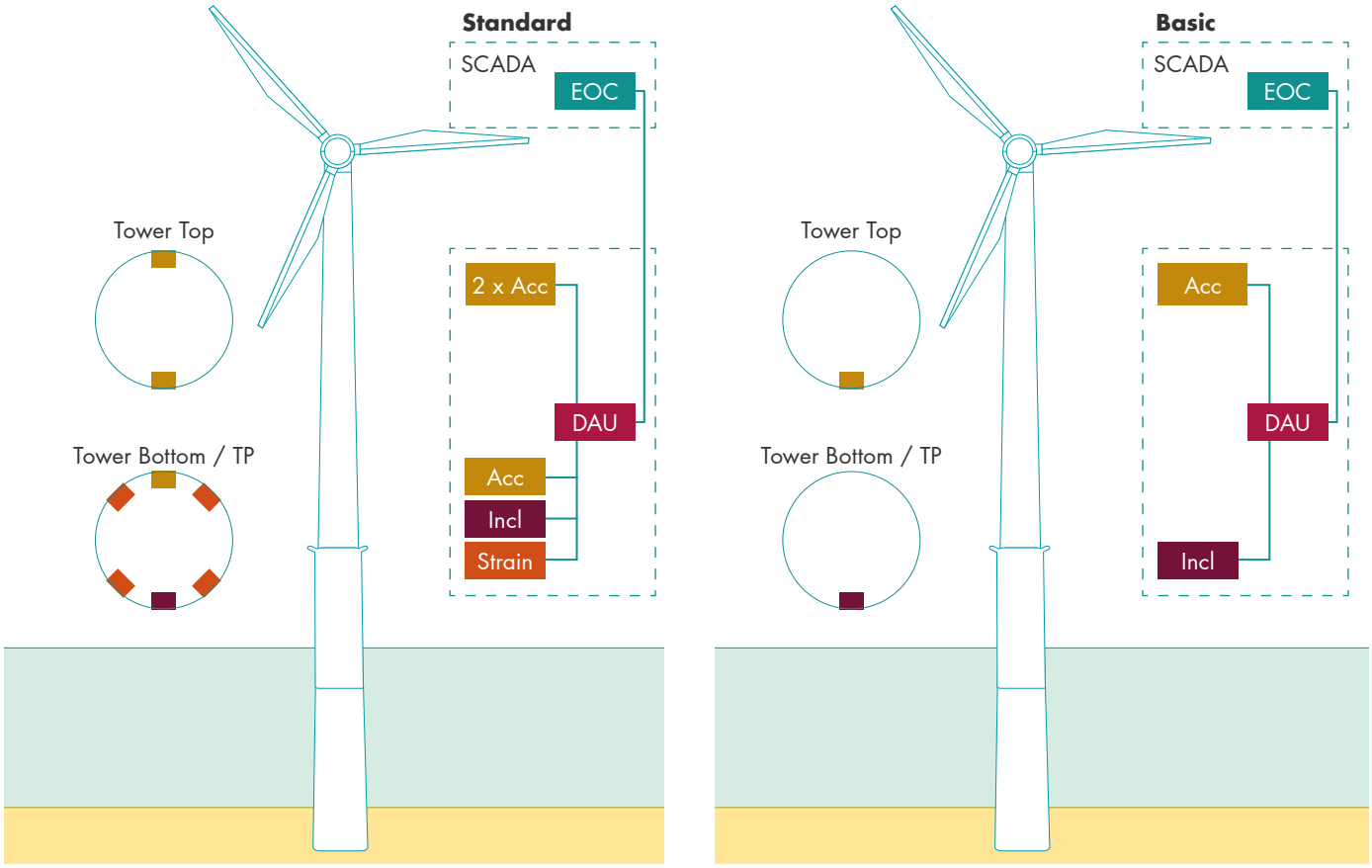


Figure 1: Proposed standard and basic sensor configurations with an optimal investment-to-value ratio. The final configuration for a given offshore wind farm might vary due to individual monitoring requirements.

The Bundesamt für Seeschifffahrt und Hydrographie (BSH) requires an SHM system individually designed for each windfarm in accordance with the requirements of the geotechnical experts. For these WTG we offer our standard solution with an optimal investment-to-value ratio. Nevertheless, our SHM approach allows you to expand the extent of your SHM coverage to a 100 % of the WTG with a basic sensor setup that uses advanced algorithmic methods to transfer the knowledge from the standard equipped turbines to all WTG in the wind park.

From Data Acquisition to Certification Authority – the SHM Process

The success of any SHM solution is firmly linked to having a reliable partner that understands the SHM process as a long-lasting commitment throughout the whole operational lifetime of the wind park.

Wölfel Supports the SHM Process in All Its Phases

Phase 1. Planning your SHM solution | We understand that the challenge of providing valuable structural insights begins with the optimal choice of sensors, their meaningful positioning and a reliable data acquisition. At the same time we take into account budgeting and non-technical constraints to find the best SHM solution. Therefore we have optimized our hardware solutions and sensor choices to reach an optimal level between investment cost and engineering value. Supported by our extensive experience developing algorithms and analysing sensor data, we are able to minimize the amount of required sensors to fulfil all the customer's monitoring goals.

Phase 2. Installation and commissioning | Wölfel has experienced engineers and technicians that are Health Safety Environment (HSE) trained to install and commission the SHM hardware at the foundation supplier factory and within the offshore windfarm. We have developed a hardware that is adoptable to all kind of electrical and network interfaces to be installed at any windfarm structure. In advance to the installation, method statements and risk assessments will be individually worked out together with the client to guarantee a safe and smooth installation. Often the offshore commissioning can take place partly remotely to safe costs and time.

Phase 3. Deployment of the SHM software and baseline definition | After installation and commissioning of the SHM hardware (sensors, servers, IT connectivity), the collection of raw data begins. During the first months of operation, all raw data is pre-processed and analysed by our experts to ensure data consistency, signal quality and to perform required calibrations and offset corrections. The results of these initial evaluations provide a baseline for the future operation and are generally used as basis for the definition of meaningful alarm criteria assessed in cooperation with the operator. This period can take up to one year.

Phase 4. Live monitoring | After the deployment and configuration of the SHM software the operational phase of the SHM begins. From this moment on, the SHM will be providing regular updates of all defined Key Performance Indicators (KPI) and checking against defined thresholds. This live monitoring phase is supported by our Wölfel Monitoring Modular

Framework, which provides a state-of-the-art technology framework to store, analyse, visualize and report about the data collected by the SHM system. A deep dive into the capabilities of this framework is provided in chapter "Wölfel's Monitoring Modular Framework".

Phase 5. Periodic reporting | Normally, detailed engineering reports – analysing the structural behaviour and assessing it against design assumptions – are required on a regular annual basis. Once the SHM system is setup, all results are synchronized with our engineering center, where reports are issued automatically and can be reviewed and commented by our experts before submission to the certification authorities.

Phase 6. Engineering support | Sometimes things do not go as planned and our SHM system identifies assets that require further attention. In these situations our engineers stand side-by-side with the operations team of the wind park – and sometimes the certification authorities – to locate the problem, recommend measures and adapt the SHM system to new requirements.

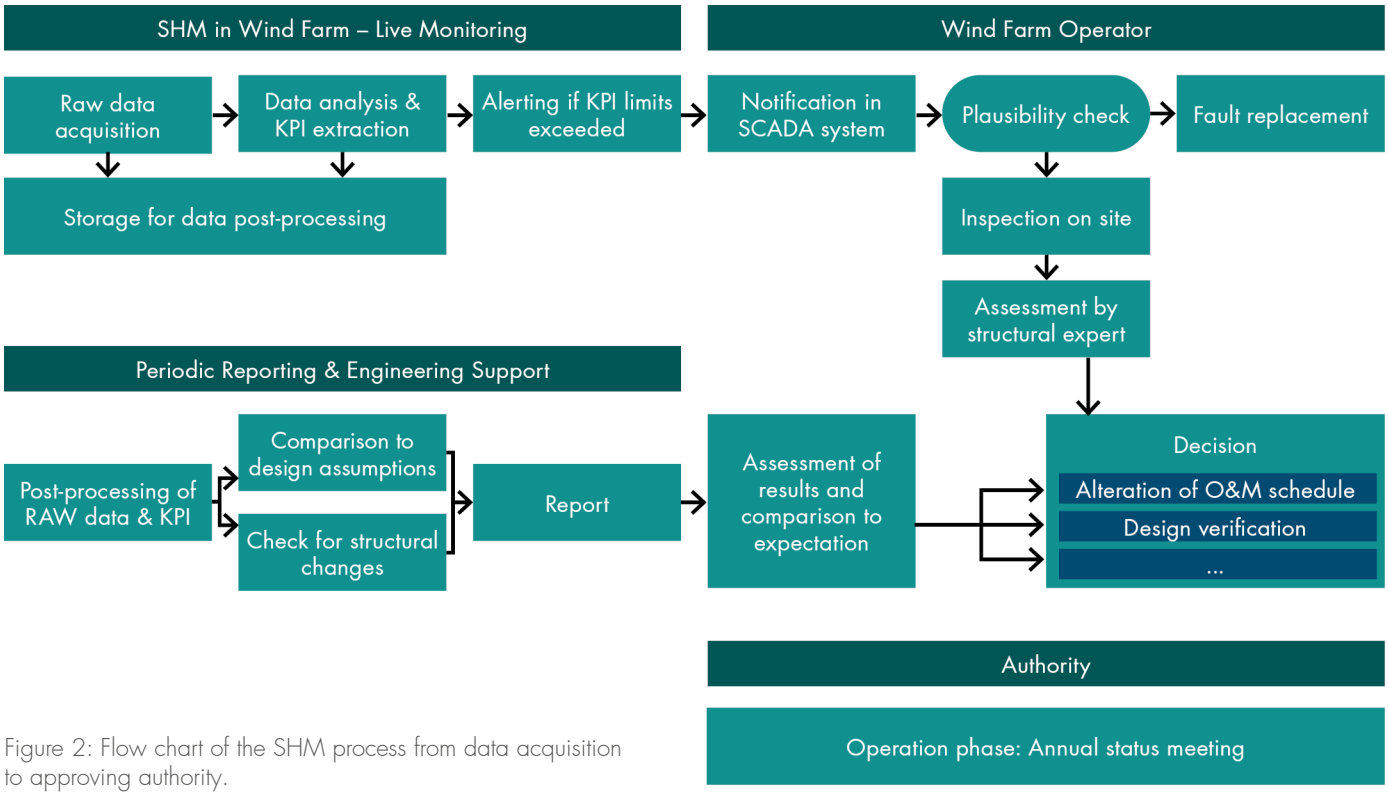


Figure 2: Flow chart of the SHM process from data acquisition to approving authority.

Wölfel's Monitoring Modular Framework

The Wölfel Monitoring Modular Framework (WMMF) is a collection of software modules designed to create custom SHM solution architectures. This specialized framework provides the basis to all software implementations required throughout the lifetime of the SHM application. The WMMF's modular concept has the following key advantages:

- High adaptability to create individual solutions according to the exact client needs.
- Expand-on-the-go: structures change and monitoring needs evolve, so does our software. Scaling the scope of our data analytics services is as easy as it gets. The customer can decide at a later stage of the project to go from a pure data acquisition solution to a full SHM solution.
- Easy integrability in the customer's IT-infrastructure by using state-of-the-art, secure communication protocols: ssh, https, sftp, s3, modbus, grpc, ...
- Fast recoverability after unexpected incidents or hardware exchange: our whole deployment is backed up and ready to deploy within minutes.
- Monitored 24/7: all software modules have their own "monitoring system" in the background and are continuously checked in terms of functionality.

This framework provides a reliable solution for any SHM application by providing state-of-the-art solutions for the data storage, analysis, visualization and reporting as described here:

Data Storage Module

Our Data Storage Module offers safe, durable and virtually unlimited storage for all data in monitoring projects. This module offers different levels of synchronization and replication, allowing the client to choose among different desired retention policies at each node and safety levels to minimize the risk of data loss. The data are synchronized over a private VPN connection and (if required) stored in a secure cloud data center in Europe, in compliance with DSGVO standards.

Our storage service provides the following key features:

- Accessibility: all data are accessible with individual secure keys. Manual downloading and uploading of data is possible via user interface. For task automation, different kinds of communication protocols are supported, including S3, sftp and ftps.

- Durability (= rate of stored data loss): our storage follows the so called rule of 11 9's, meaning the durability is 99.999999999 %, meaning "if you store 10,000,000 files on our storage, you can on average expect to incur a loss of a single object once every 10,000 years". Additionally, we put in place measures against accidental deletion and file versioning.

- Availability: when a single storage region is used to store your data, we offer a system availability of 99.9 %. When you store your data across two storage regions, we offer a system availability of 99.99 %.

Note
For on premise deployments at the client's infrastructure, the client has to account for high outgoing data volumes.

Data Analytics Module

Our Data Analytics Module offers custom advanced analysis possibilities powered by Matlab. This module is designed for the batch analysis of high frequency data (up to 10 kHz) from multiple data sources with a focus on speed and functional versatility for engineering applications. Wölfel's specialized libraries for mechanical and structural analysis allow for specialized analyses such as SSI (Stochastic Subspace Identification), load reconstruction, fatigue analysis (GL DNV, DIN EN), sensor virtualization (using a Finite Element Model), normative evaluations (VDI3834) and more.

Some SHM Functionalities Featured by Our Data Analytics Module Are:

Pre-processing: Data quality and statistics

Our software includes advanced data quality checks, correction of sensor offsets, calibration and temperature compensation of strain gauges and general statistical analysis.

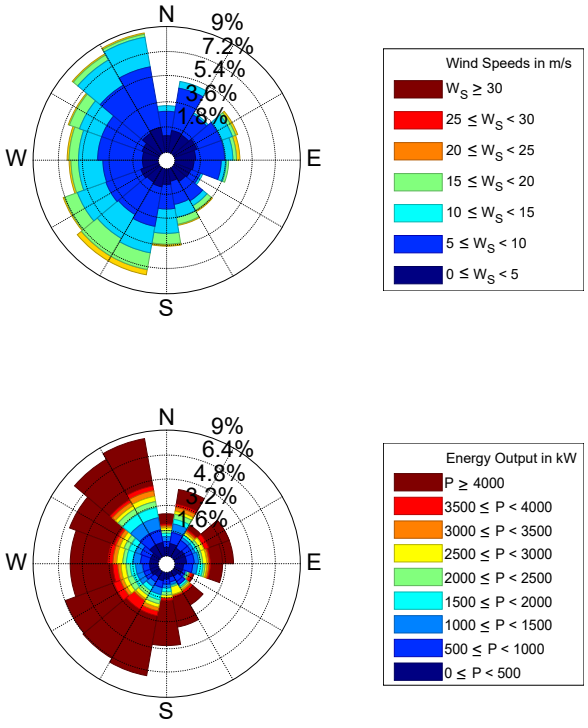


Figure 3: Exemplary analysis of wind direction distribution and energy output. Data source: internal.

Operational modal analysis and anomaly detection

Detecting structural changes based on the variation of the dynamic properties is a common requirement in SHM applications. Our Data Analytics Module offers state-of-the-art algorithms for the continuous extraction of the modal features (eigenfrequencies, damping ratios and mode shapes).
The modal properties of a WTG change depending on its operating state. Therefore, the goal of an SHM system is not to detect change, but to detect anomalies, that is, changes in the dynamic behaviour that can not be explained by the current operation of the system. Solving this problem requires the use of advanced training algorithms, in which our software learns the correlation between operational states and modal features. After an initial training phase of 3 to 6 months, our software is able to reliably detect structural anomalies.

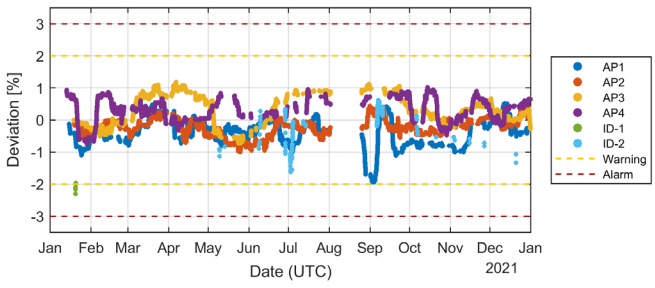


Figure 4: Exemplary analysis of deviations of the first eigenfrequency vs design, classified by different operational states. Data source: internal.

Load reconstruction and lifetime assessment

Our Data Analytics Module features algorithms to continuously monitor acting loads at critical sections of the structure and perform fatigue lifetime assessments. Our software supports two common approaches for the load determination at relevant cross-sections:

- Direct measurement with strain gauges:
  The most accurate approach for the measurement of bending moments at the reference cross-section consists of the direct measurement of longitudinal strains along its circumference. This methodology requires the calibration of the strain gauge offsets by means of a nacelle rotation in non-operational, low wind conditions.

- Indirect measurement with virtual sensors:
  The determination of bending moments is possible based on virtual sensors derivated from accelerometer measurements. In order to do that, a Finite Element (FE) model of the system has to be used, which provides the knowledge about the mechanical coupling between the different locations of the structure. Due to the introduction of an engineering model in this concept, the results are less accurate than the ones from a direct strain measurement. However, using a model introduces an additional flexibility, allowing us to virtualize an arbitrary number of measuring locations.

The Continuous monitoring of internal forces (mostly bending moments) is necessary for their health assessment during extreme events (ULS) and for evaulating cumulative fatigue damage throughout their operation lifetime (FLS). Given the large number of structural components and fatigue details present in the foundation and tower of the WTG, it is common practice to focus on monitoring a single cross-section, typically at the height of the transition between tower and transition piece. This "reference" cross-section is well characterized in the design documents with regards to ultimate and fatigue loads and allows for a quantitative comparison between design and measurements. While the assessment in the ULS is based on the direct comparison between measured and allowable maximum bending moments at this reference cross-section; the assessment of the FLS requires a derivated magnitude, the so-called Damage Equivalent Loads (DEL), which accounts for the loading cycles and fatigue cummulation, by including rainflow counting and Palmgren-Miner's accumulation in its formulation.
The biggest advantage of using DEL both during design and monitoring is that it provides a normalized fatigue damage, easy to compare quantitatively, which can be referred to any fatigue detail a posteriori given a specific Wöhler curve.
Wherever possible, our SHM applications rely on direct strain gauge-based measurements to establish a reference benchmark for the calibration of the virtual loading sensors and their FE model. During the operational life of the strain gauges, their results are used by the SHM application both for monitoring purposes and for training of the virtual sensors. The results of this training are regularly transmitted to all locations, i.e. all turbines of a park profit from the knowledge of few turbines with "expensive" strain-gauge instrumentation.

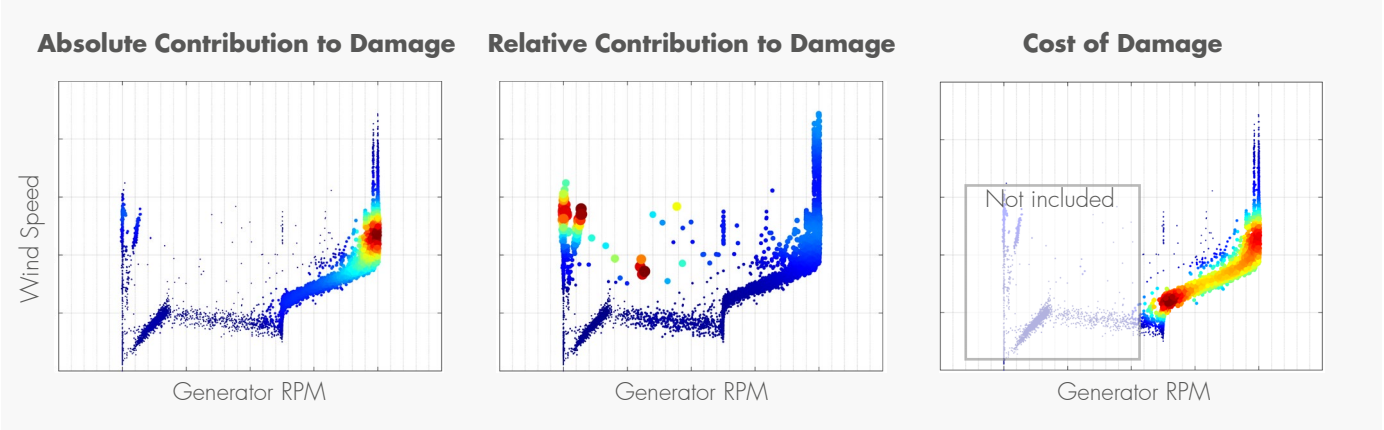


Figure 5: Exemplary analysis of cumulated damage from an operational perspective. Left: absolute damage contribution. Middle: relative contribution (cumulated damage / number of occurrences). Right: cost of damage (cumulated damage/energy yield), Data source: [1]

Vibration assessment and anomaly detection

One simple but efficient way to evaluate the health state of the WTG consists of evaluating its vibration levels, such as recommended in the VDI3834 guideline.

With our Data Analytics Module, accelerations at tower top are not only used for normative evaluations, but also to identify torsional and flexural vibration components. Additionally, using our advanced training and anomaly detection algorithms, rotor imbalances and unexpected operational conditions can be reliably detected.

Population assessment

After extracting SHM results for each individual turbine, population analyses can be performed. They provide especially valuable insights into the global performance of the wind park and allow for the identification of "black sheep" in your fleet.

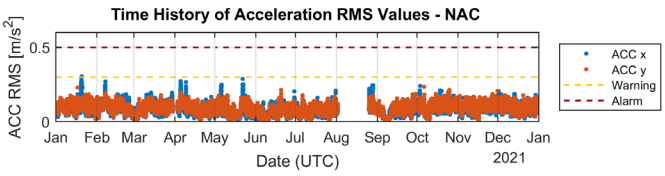


Figure 6: Exemplary evaluation of tower top vibrations according to VDI 3384. Data source: internal.

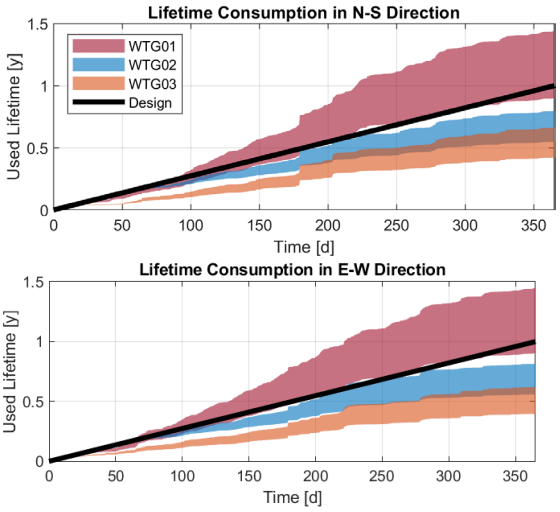


Figure 7: Exemplary comparison of the evolution of lifetime consumption between three WTG in the same wind park. WTG01 requires further attention. Data source: [1]

MIC® Visualization Module

The Monitoring Intelligence Center (MIC®) Module offers modern web-based UI for managing, supervising and analysing the status of your SHM application. MIC® can be deployed in a wide range of network environments (from local networks to cloud environments with secured access) and offers a highly customizable interface. Within minutes, the client is able to generate customized dashboards communicating seaminglessly with our database in the backend without the need of scripting or advance query language knowledge.

Some of the Key MIC® Features Are:

- user management and permission system with three roles (admin, editor, viewer)
- alerting engine with custom definition of criteria and notification channels (email, push notification, …)
- secure authenticated access over https
- data export functionality

Reporting Module

In many projects, both customers and other stakeholders, such as certification bodies, are interested in receiving regular updates about the state of the structure.
Our Reporting Module offers the possibility of generating reports on any regular basis (from daily to yearly) in PDF format. Depending on the customer requirements, these reports range from one-page automated status reports to fully-reviewed health assessment reports, commented by our expert engineers and ready for delivery to certification authorities.

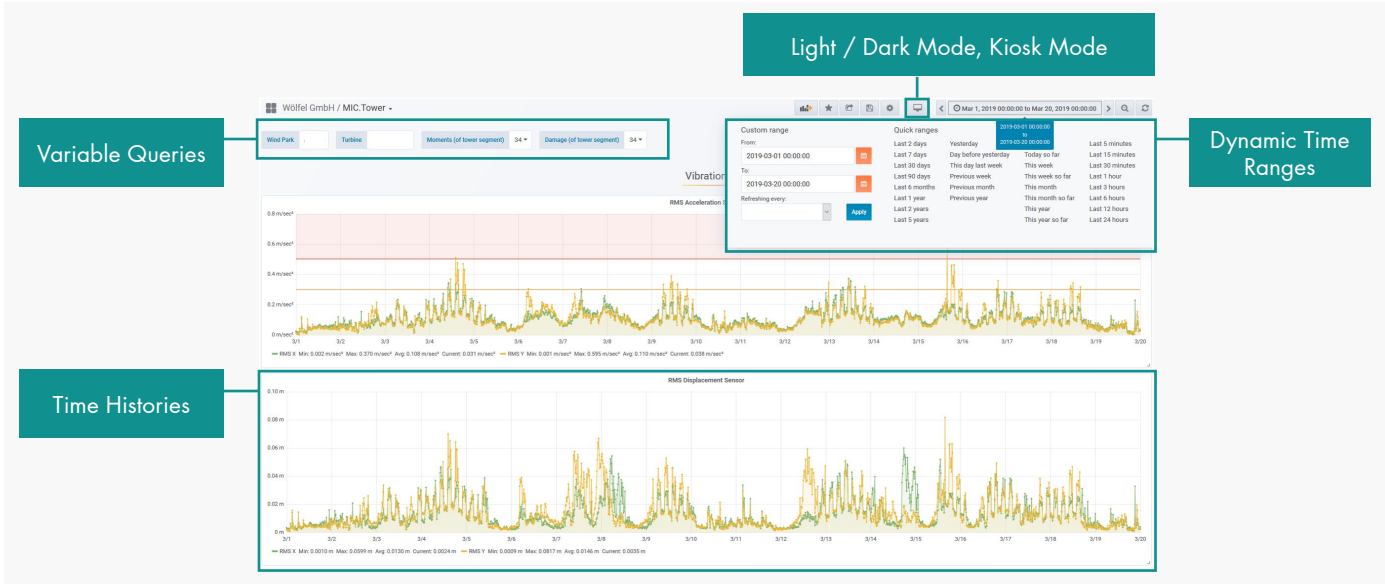


Figure 8: Dashboard example from the MIC.Foundation web platform with a description of certain elements.

[1] Schwingungsbasierte Lastrekonstruktion an Gründungsstrukturen von Offshore-Windenergieanlagen onlinelibrary.wiley.com/doi/10.1002/bate.202200037

Overview References Offshore Wind

	Nordsee Ost, Germany	Amrumbank West, Germany	Wikinger, Germany	Arkona Becken, Germany	Alpha Ventus, Germany	Helwin Alpha, Germany	Merkur, Germany	Deutsche Bucht, Germany	TWB II, Germany	Yunlin Windpark, Taiwan	Galloper, UK	Friesland, The Netherlands	St. Brieuc, France
Client	RWE	RWE	IBERDROLA	RWE	DOTI	Tennet	Merkur	Northland Power	EWE	Skyborn Renewables	RWE	Von Oord	IBERDROLA
Start	2014	2015	2015	2015	2016	2016	2017	2017	2018	2019	2019	2020	2020
WEA	48 Senvion 6.2 MW	80 Siemens 3.6 MW	70 Adwen 5 MW	60 Siemens 6 MW	12 Areva Repower	576 MW	66 GE-Hal. 6 MW	31 Vestas 8.4 MW	32 Senvion 6.3 MW	80 Siemens 8 MW	56 Siemens 6.3 MW	89 Siemens 4.3 MW	62 Siemens 8 MW
Foundation Structure	Jacket	Monopile	Jacket + OSS	Monopile + OSS	Jacket + Tripod	Offshore Plattform	Monopile	Monopile	Monopile	Monopile	Monopile	Monopile	Jacket
Monitoring concept	✓	✓		✓	✓	✓	✓	✓	✓			✓	
Hardware design	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Installation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Data Processing	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Data Analysis	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
BSH reporting	✓	✓	✓	✓	✓	✓	✓	✓	✓				
Fleet Monitoring for all structures		✓		✓				✓	✓				
Lifetime Management	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		

	Kaskasi, Germany	Sylwin Alpha, Germany	Arcadis Ost 1 – OSS, Germany	Hollandse Kust South, Netherlands	Morray West; UK	Sofia, UK	Hai – Long, Taiwam	Jeonnam 1, Korea	Costal Virginia, USA	Thor – OSS, Denmark	Nordsee Cluster, Germany	Baltic Eagle, Germany
Client	RWE	Tennet	Parkwind	Vattenfall	Morry West	Van Oord/ RWE	Northland Power	CPI	DOMINION Energy	RWE	RWE	IBERDROLA
Start	2020	2020	2021	2021	2022	2022	2022	2022	2023	2023	2024	2024
WEA	38 Siemens 8 MW	864 MW	27 Vestas 9.5 MW	140 Siemens 11 MW	60 Siemens 14.7 MW	100 Siemens 14 MW	73 Siemens 14 MW	15 Siemens 5 MW	180 Siemens 14 MW	OSS	104 Vestas 15 MW	50 Vestas 9.5 MW
Foundation Structure	Monopile	Offshore Platform	Monopile	Monopile	Monopile	Monopile	Jacket	Monopile	Monopile	Jacket	Monopile	Monopile
Monitoring concept		✓					✓	✓			✓	
Hardware design	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Installation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Data Processing	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Data Analysis	✓	✓	✓				✓	✓			✓	✓
BSH reporting	✓		✓								✓	✓
Fleet Monitoring for all structures							✓	✓				
Lifetime Management	✓		✓				✓	✓				✓

Quality, Health and Safety, Environmental Protection

The Wölfel Group is pleased to announce its notable certifications and accreditations, reflecting the organization's dedication to excellence and adherence to international standards. The following achievements of Wölfel Engineering GmbH + Co. KG highlight their commitment to quality and proficiency:

- Certification according to DIN EN ISO 9001:2015:
  Wölfel Engineering GmbH + Co. KG and Wölfel Wind Systems have been certified for its comprehensive capabilities in consulting, design, analysis, measurement and development, manufacturing, and sales of systems in strength of materials, dynamics, and acoustics for mechanical, civil and plant engineering.
  This certification underscores the company's commitment to meeting stringent quality standards. Certificate Registration No: 04 100 020955.

- Certification according to DIN EN ISO 45001:
  Wölfel Group has obtained certification according to DIN EN ISO 45001, highlighting their commitment to occupational health and safety management systems.

- Certification according to DIN EN ISO 14001:
  Wölfel Group has obtained certification according to DIN EN ISO 14001, demonstrating their dedication to environmental management systems.
  This certification reflects the organization's holistic approach towards prioritizing environmental protection, and operational excellence.

- Accreditation according to DIN EN ISO/IEC 17025:2018:
  Wölfel Engineering GmbH + Co. KG has received accreditation for its proficiency in testing across various fields. Their expertise encompasses the determination of noise and vibrations, noise measurements at wind turbines, noise and vibrations at workplaces, aircraft noise, building acoustics, and module immission control. This accreditation with DAkkS Registration-No. D-PL-19254-01-00 enhances the organization's credibility and reliability.

- Official acknowledgment as a measuring Institution:
  Wölfel Engineering GmbH + Co. KG has obtained official recognition in Bavaria and other federal states as a measuring institution in accordance with § 29b BImSchG (Federal Immission Control Act). This recognition enables the organization to assess

emissions and immissions resulting from noise and vibrations. Additionally, they have received confirmation of suitability for quality assurance, conforming to the standard KTA 1401.

- **Certification for quality inspections:** Wölfel Engineering GmbH + Co. KG holds certification for conducting quality inspections in the field of noise insulation, according to DIN 4109. Their registration no. VMPA-SPG-210-04-BY in the directory of VMPA noise control test facilities, published by VMPA (German Association of Material Testing Institutes), further establishes their expertise in ensuring adherence to noise insulation standards.

Furthermore, the organization demonstrates conformity in the measurement of sound emission values of wind turbines, following the Technical Guidelines, part 1, of Fördergesellschaft Windenergie (FGW). This commitment exemplifies Wölfel Group's dedication to promoting sustainable and environmentally friendly solutions.

Wölfel Group remains committed to upholding and advancing its certifications and accreditations, demonstrating an ongoing pursuit of excellence and a steadfast commitment to delivering exceptional services to clients.

Wölfel Wind Systems – Offshore Team

Wölfel Engineering GmbH + Co KG is a research-intensive small and medium-sized enterprise (SME) and holds the position of being the largest company within the Wölfel Group. Over one third of the group's 100+ colleagues possess a PhD in engineering or natural sciences.

Wölfel specializes in offering engineering services in the field of structural mechanics, with a particular emphasis on dynamics. The company's notable success is largely attributed to its rapidly expanding wind energy division, which primarily focuses on offshore operations. This division has evolved from two national German R&D projects and has become a significant contributor to the company's overall achievements.

Dr.-Ing. Carsten Ebert

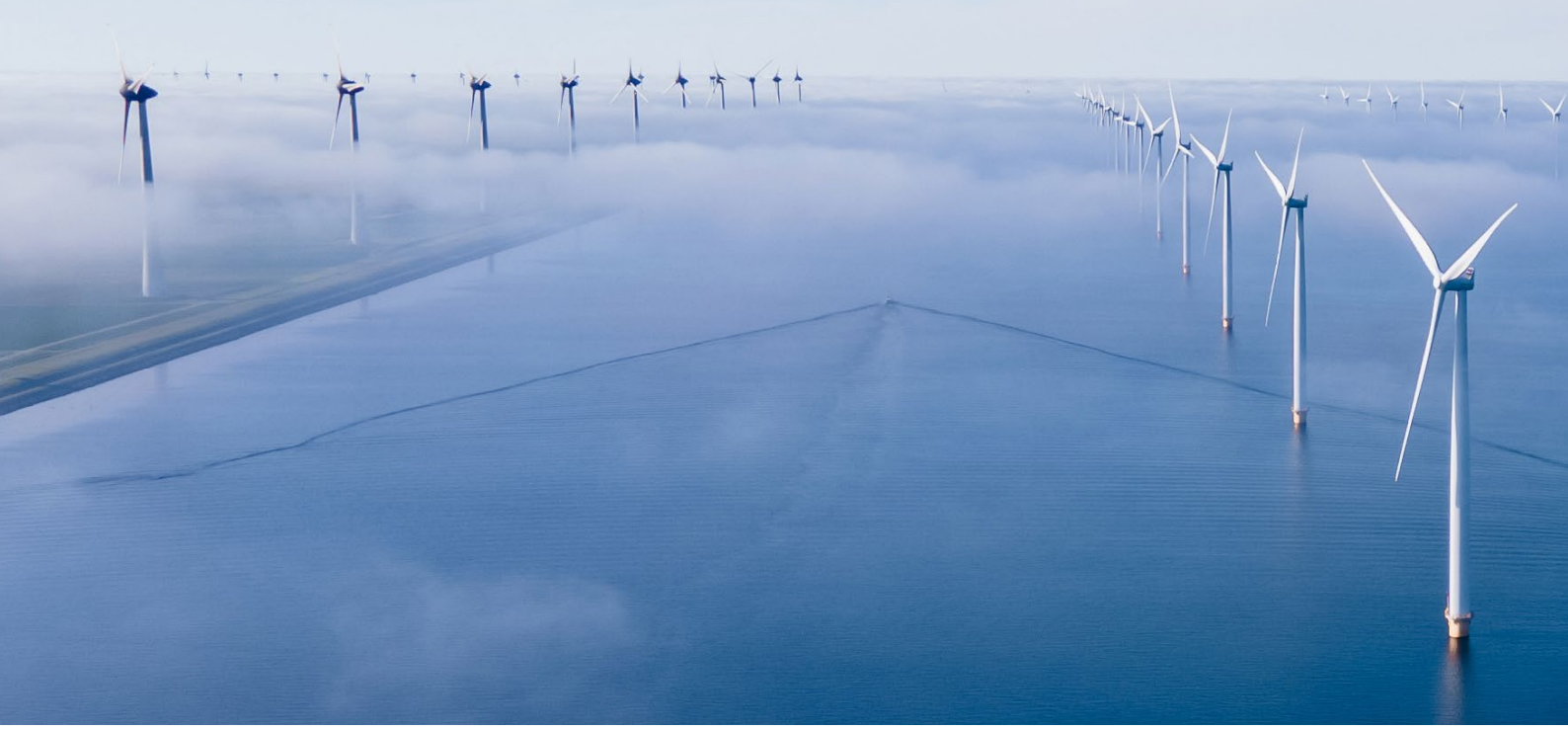
- **CTO** of Wölfel Wind Systems GmbH + Co. KG
- **Civil Engineer** (M.Sc.) by the Leipzig University of Applied Sciences; focus on structural engineering
- **PhD in the field of structural dynamics** in cooperation between University of Siegen, Prof. Fritzen and Leipzig University of Applied Sciences, Prof. Lenzen
- **Committee activities:**
  - DIN 4150, Parts 1 and 3: "Vibrations in buildings" (German standard)
  - VDI 4551: "Structural monitoring and assessment of wind turbines and offshore stations" (German standard)
  - IEA Wind, Task 42: "Wind Turbine Lifetime Extension"
- **+ 20 years' experience** in structural dynamics and SHM

Dipl.-Ing. Bernd Wölfel

- Shareholder of the Wölfel Group
- **Head Offshore Wind:** Establishment and development of the Hamburg branch office with focus on the wind energy sector of Wölfel
- **Civile Engineer** by TU Berlin (background of foundation engineering and soil mechanics)
- **+20 years´ experience** in the construction and offshore wind industry
- **Committee activity:** Committed to the German offshore wind industry and actively represented at WAB

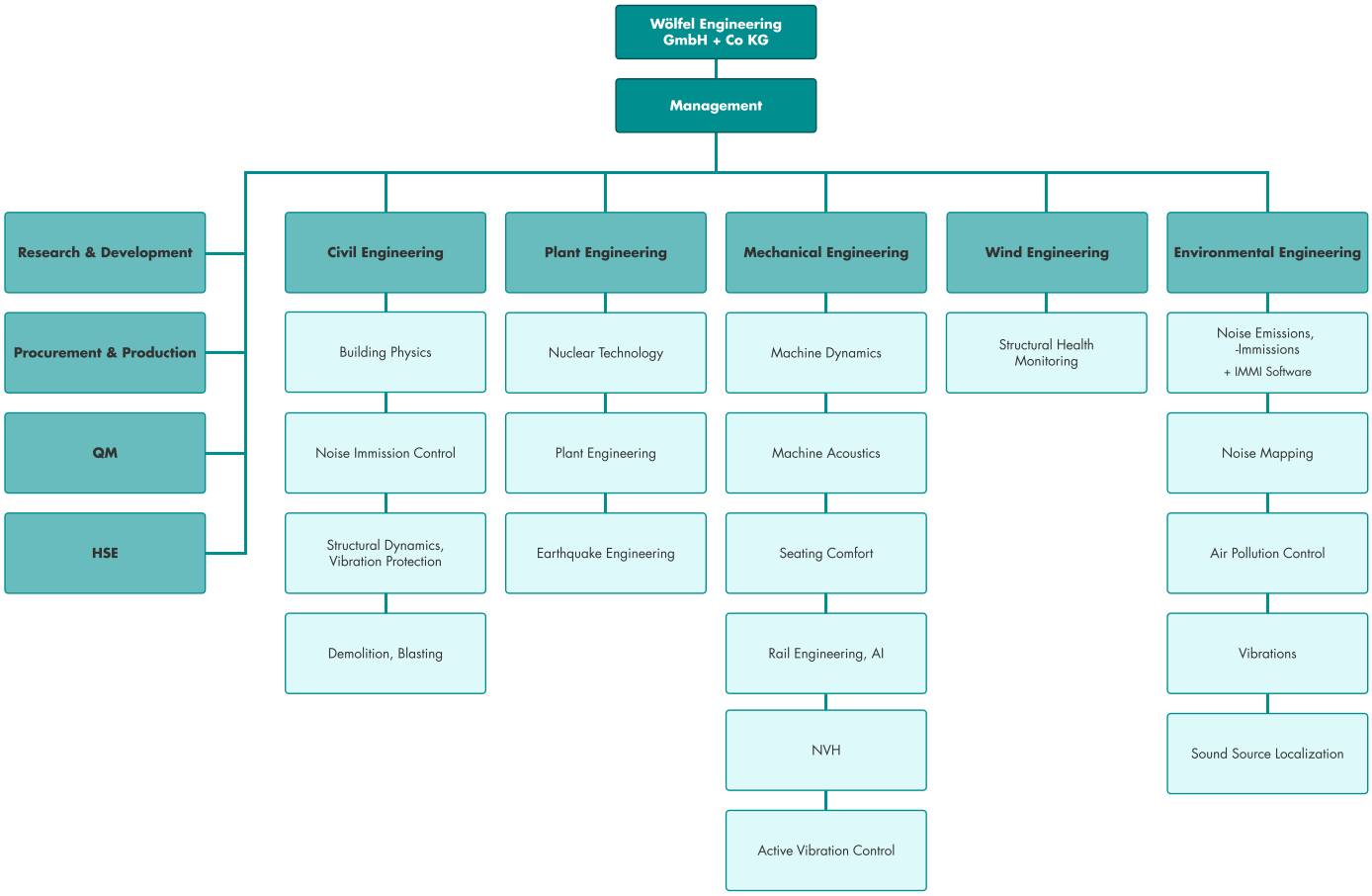
Dr.-Ing. Carles Colomer Segura

- Head of Development Monitoring Systems
- **Civil Engineer** by the Universidad Politécnica de Valencia (focus on structural mechanics and dynamics)
- **PhD at the Institute for Steel Construction** at the RWTH Aachen
- **Guest Lecturer** at University of Siegen in cooperation with Prof. Peter Kraemer (Chair of Mechanics and Structural Health Monitoring)
- **+ 15 years' experience** in structural dynamics and SHM

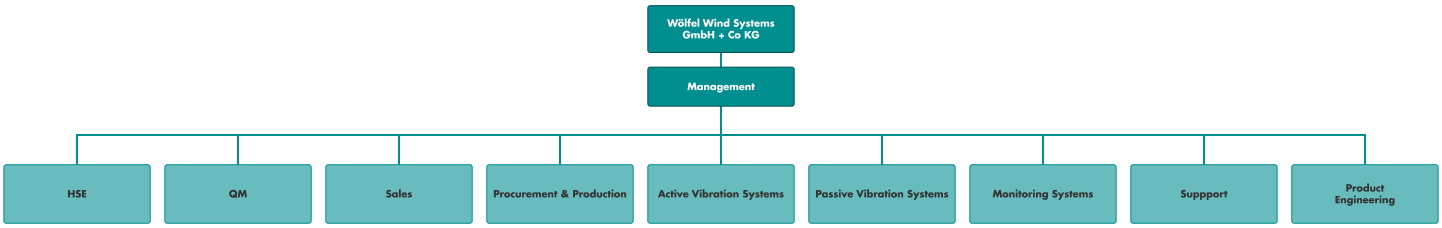


Wölfel organization chart

Wölfel Engineering



Wölfel Wind Systems



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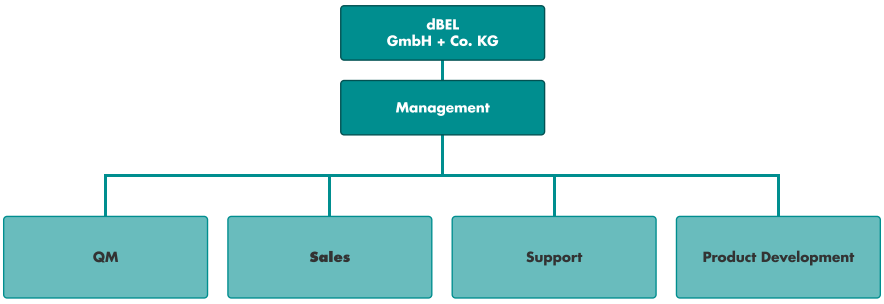
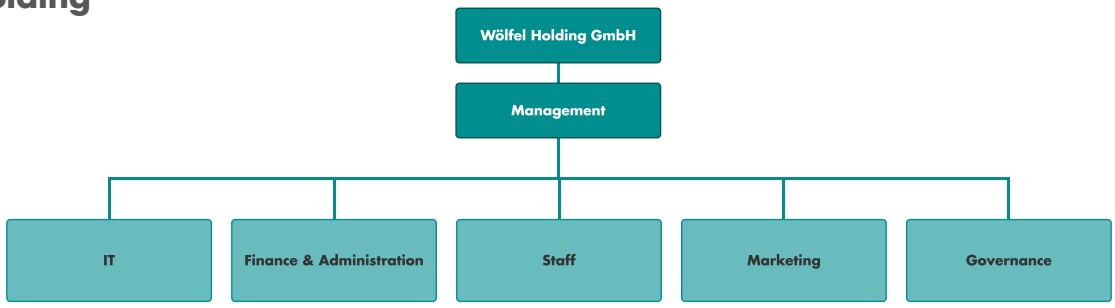
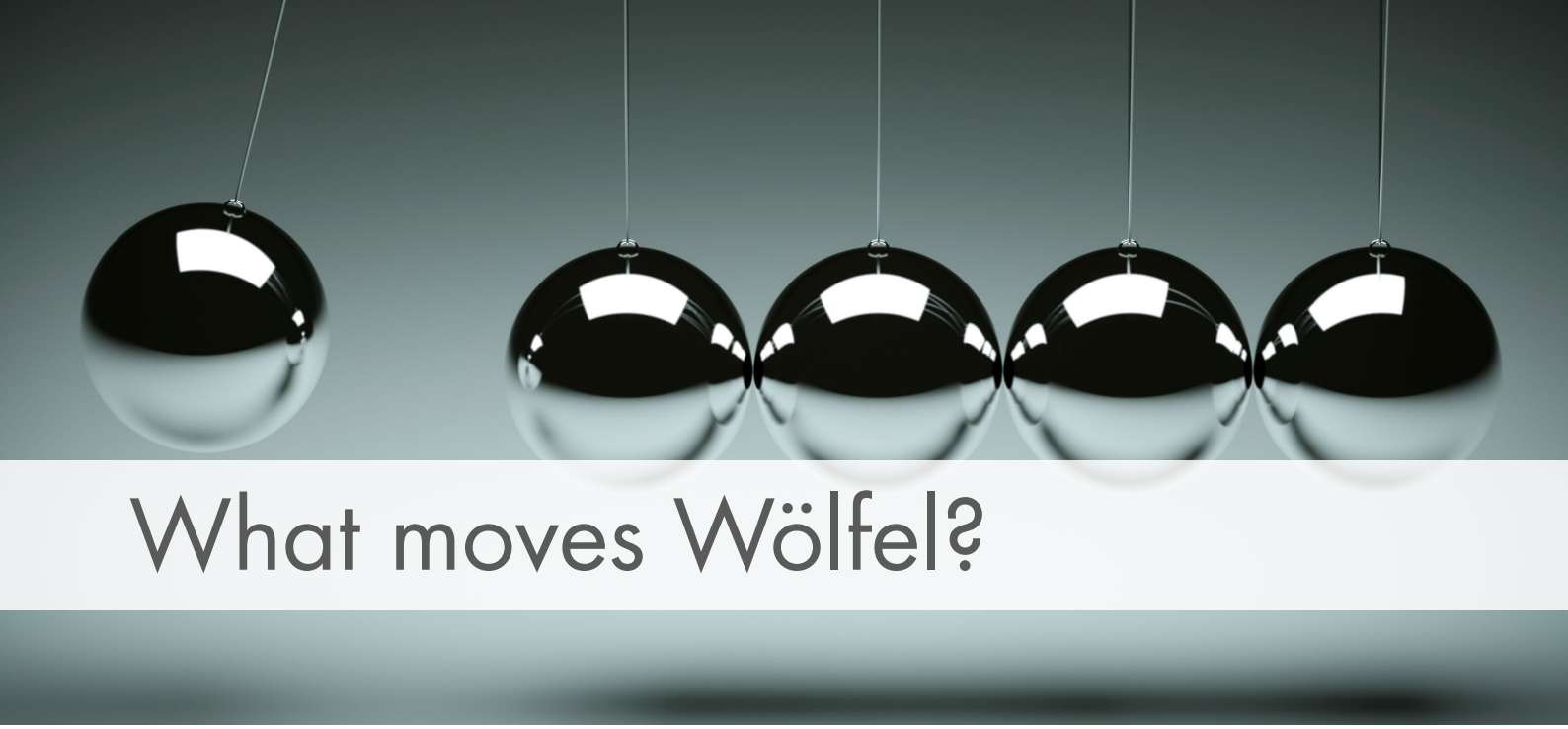


Wölfel Holding





What moves Wölfel?

Vibrations, structural mechanics and acoustics – this is the Wölfel world. Here we are experts, this world is our home. More than 140 employees daily do their best for complete satisfaction of our customers. For more than five decades we support our customers with engineering services and products for the analysis, prognosis and solution of tasks in the fields of vibrations and noise.

Are vibrations really everywhere? Yes! That's why we need a wide variety of solutions!
Whether it is engineering services, products or software – there is a specific Wölfel solution to every vibration or noise problem, for example

- simulation-based seismic design of plants and power stations
- measurement of acoustic emissions of wind turbines
- universal measuring systems for sound and vibrations
- expert reports on noise immission control and air pollution forecasts
- dynamic occupant simulations for the automotive and aviation industry
- and many other industry-specific Wölfel solutions …

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Wölfel
Developing people. Engineering the future.