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FIBREGY

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Development, engineering, production and life cycle management of improved FIBRE-based material solutions for the structure and functional components of large offshore wind enerGY and tidal power platforms

D4.8 (WP4): Report on recommendations for predictive maintenance

Responsible Partner: TSI

Contributor(s): TSI, ENEROCEAN, BV, CIMNE, COMPASSIS

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Author	Cristobal Garcia Pariente	TSI	18.06.2023	

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EXECUTIVE SUMMARY

The main purpose of a Structural Health Monitoring (SHM) System is to detect changes in the structural condition of Offshore Turbine Platforms that represent deviations from the normal operational behaviour and therefore, indicate the existence of developing faults.

Based on an extensive review of the state of the art, this study gives insight into predictive maintenance procedures for Floating Offshore Wind Turbines and Tidal Turbines built in FRP materials (See Section 2). To simplify the handling of the document, the procedures have been classified as Condition Based Maintenance (CBM) procedures for inspection and maintenance of the drivetrain and gearbox as well as Structural Health Monitoring (SHM) procedures for O&M of the tower, floating platform, and mooring lines.

In addition, Section 3 provides a list of guidelines and standards for OWTPs based on the input of end-users for predictive maintenance. The list of standards provides standards from reputed classification societies such as Bureau Veritas and Det Norske Veritas along with standards from international organizations such as International Organization for Standardization (ISO), and International Electrotechnical Commission (IEC), among others.

Eventually, Section 4 sheds light on the Structural Health Monitoring system installed for the inspection and maintenance of FRP-based towers of the W2Power Wind Turbine. The diagnosis of the towers is based on a series of key performance indicators (KPIs), which provide real-time information about the damage state and structural condition of the structural components of the tower. Special attention is also paid to the optimum number and location of the sensors to be installed in the tower as well as the definition of the data comunication system and the monitoring cabinet.

Another aspect addressed in Section 5 consists of the definition of a list of Key Performance Indicators to be processed during the sea test trials in the Canary Islands. The mechanism for damage detection is based on the shift of the Key Performance Indicators due to the presence of the defects.

The last section of the document offers some conclusions as well as future steps for further research and development of this innovative technology (see Section 6).

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NOMENCLATURE / ACRONYM LIST

Acronym	Meaning
AE	Acoustic Emission
CBM	Condition Based Maintenance
DAS	Digital Adquisition System
DNV	Det Norske Veritas
FFT	Fast Fourier Transform
FOS	Fibre Optic Sensor
FOWT	Floating Offshore Wind Turbine
IEC	International Electrotechnical Commision
IMU	Inertial Measurement Unit
ISO	International Organization for Standarization
KPI	Key Performance Indicator
PLOCAN	Oceanic Platform of the Canary Islands
OWTP	Offshore Wind and Tidal Plants
ROV	Remote Operating Vehicle
SCADA	Supervisory Control and Data Acquisition
SHM	Structural Health Monitoring
VDI	Verein Deutscher Ingenieure
VSHM	Vibration-based Structural Health Monitoring
WiMAX	Worldwide Interoperability for Microwave Access
ULS	Ultimate Limit State

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1. INTRODUCTION

The maintenance strategies for Floating Offshore Wind Turbines (FOWTs) and Tidal Plants can be divided into three main categories referred to Corrective, Preventive, and Predictive Maintenance.

- Corrective Maintenance: It consists of running to failure and subsequently performing repairs. This technique has the limitations of long downtimes and no possibility to be scheduled.
- Preventive Maintenance: This technique consists of regular inspections of the critical components of the turbine which are performed at scheduled times (e.g. every year, five years, etc...).
- Predictive Maintenance: It is based on the information collected by means of a condition-based monitoring system at fixed time intervals. The CBM system is a permanently installed monitoring equipment composed of a network of sensors distributed in critical points of the structure.

The primary aim of this report is to shed light on the definition of the SHM system developed for the inspection and maintenance of the FRP-based Towers installed in the W2Power Floating Offshore Wind Platform. To achieve this goal, an array of fibre optic sensors (FOS), strain gauges, accelerometers, gyroscopes, and inclinometers is installed in strategic positions of the tower for the collection of 10 minutes of data. Subsequently, the data acquired for these sensors is processed for the Compaq Rio Data Acquisition (DAS) System in order to obtain relevant Key Performance Indicators (KPIs) which will provide relevant information about the damaged state of the tower for relevant case scenarios. Eventually, the trend of data in the time domain together with the variations of the KPIs will be analyzed with the purpose to get valuable information about the detection, quantification, and location of defects.

The rest of the report is organized as follows:

- Section 2 provides insight into Predictive Maintenance Procedures for Floating Offshore Wind Turbines and Tidal Turbines built with FRP materials. For such purpose, an extensive review of the state of the art of Structural Health Monitoring (SHM) and Condition Based Monitoring (CBM) systems for Offshore Wind Turbines and Tidal Plants (OWTPs) is presented in the document.
- Section 3 provides a list of classification society and international standards for OWTPs based on the input of the end users. This information is used as starting point for the definition of the Structural Health Monitoring System.
- Section 4 sheds light on the Structural Health Monitoring system installed for the inspection and maintenance of FRP-based towers of the W2Power Wind Turbine. As stated above, the diagnosis of the towers is based on a series of key performance indicators (KPIs), which provide real-time information about the damage state and structural condition of the tower.
- Section 5 provides conclusions and future steps for research and development of this innovative technology.

2. PREDICTIVE MAINTENANCE FOR OWTPs

Monitoring consists of continuously recording a series of Key Performance Indicators (KPIs) to verify the damage status of a system by the comparison between the measured and reference values. As a general rule, the monitoring of structural components is referred to as Structural Health Monitoring (SHM), while the monitoring of rotative components is known as Condition Based Monitoring (CBM).

To elaborate on this section, a comprehensive review of the monitoring principles used for the inspection and maintenance of offshore and onshore wind turbines has been addressed based on an extensive review of the state-of-the-art, standards, and commercial systems. Here below, it is described relevant KPIs for CBM systems in Drivetrain and Gearbox, as well as SHM systems for rotor blades, tower, foundation, floater, and mooring lines along.

2.1. CBM of Drivetrain and Gearboxes

The most common condition-based monitoring techniques for the assessment of drivetrains are based on vibration and oil analysis.

(a) Vibration-based monitoring systems: These systems are primarily used on the market to inspect the condition of rotative components integrated into the nacelle as for example bearings, shafts, and gearwheels. The fault detection principle is based on the fact that a fault in rotating machinery leads to excessive vibration levels and specific vibration patterns.

The sensors applied for vibration-based condition monitoring include accelerometers, velocity transducers as well as displacement transducers, which are installed in critical positions in the drivetrain. For the selection of the right sensors, the parameters that need to be considered are frequency range, measurement direction, number of sensors per component, sensor sensitivity, ingress protection rate, mounting method, etc. As general conclusion, it can be said that this technology has been widely applied for the monitoring of offshore and onshore wind turbines in an Operational environment (TRL 9).

(b) Oil-based monitoring systems: Oil condition monitoring can be applied to the gearbox for two different purposes: 1st) the lubricant properties are monitored to determine the quality of the oil and therefore, provide an alarm when it is required to change the lubricant oil. 2nd) The debris content and chemical analysis of the oil can indicate the presence of faults in the gearbox and thus provide relevant information for the CBM assessment of the machinery.

Nowadays, a large number of products have been applied for the end-users for oil-based condition monitoring of the drivetrain. The parameters affecting the oil properties and therefore of interest for a Condition Based Monitoring (CBM) system can be divided into the following categories: Water ingress, Air, Particles, Oil Oxidation, Wear Debris, and Oil Temperature, among others. For example, the presence of oil debris gives an alert of the presence of damage in the gearbox based on the particle size and count of the number of particles per unit of time. Generally, trend analysis is typically used to monitor the evolution of the measured parameters over time.

Apart from the above-mentioned techniques, it has been reported alternative approaches for monitoring the condition of wind-turbine drivetrain components such as Thermography and Acoustic Emission (AE).

(c) Acoustic Emissions (AE) is a non-destructive technique based on the analysis of high-frequency transient elastic waves (20 kHz-1 MHz) that occurs when a material undergoes irreversible changes in its internal structure such as the apparition of cracks, voids, or plastic deformation.

(d) Thermography is a non-destructive technique that relies on the use of thermographic cameras for fault detection in wind turbines. The images of thermal radiation commonly known as thermograms can be potentially used to accurately identify electrical and mechanical faults of the rotative components of the drivetrain in wind turbines.

In conclusion, it is noticed that the two above-mentioned technologies (AE and Thermography) are part of research and development innovation projects and therefore, are on their way to being viable. As part of this study, the Key Performance Indicators relevant to the inspection and maintenance of drivetrains and gearboxes are detailed in the table below:

Table 1: KPIs for monitoring the drivetrain.

KPI	Description	Type of Sensor	Sensor Location
Vibration	Detect failures in the bearings, gearbosex, low / high speed shaft, etc.	Accelerometer	Radial and Axial
Density of Particles	Measure quantity of particles per unit of time and size	Wear-Debris sensors	Particle counters in oil
Stress Waves	Identification of the inception cracks and propagation	Acoustic Emission sensors	
Temperature	Detect and Measures the surface temperature of the object	Infrared Camera	

2.2. SHM of Rotor Blades

Two popular approaches for monitoring the integrity of rotor blades are vibration and strain-based monitoring as it is detailed below:

(a) One of the most intuitive methods to assess the damaged parts of Rotor Blades consist of a vibratory analysis based on Fast Fourier Transform (FFT) spectrums. In fact, the apparition of a defect increases the vibration levels of the rotative components of the system and therefore, it leads to changes in the overall vibration of the FFT spectrum.

(b) Another classical approach consist of a network of strain gauges to estimate strain concentrations at different locations of the rotor. To simplify the handling of the data, a set of statistical values such as maximum, minimum, and average strains can be calculated. Based on the strain measurements, it is possible to calculate the main stresses of the structure and to make a comparison with the Ultimate Limit State (ULS) stress.

Other less common approaches reported in the literature are based on the technique of acoustic emissions and blade deflection.

(c) Acoustic Emission (AE) refers to the radiation of acoustic waves when a material undergoes irreversible changes in its internal structure due to a crack formation or plastic deformations.

(d) The analysis of the damage state via blade deflection is based on the variations of the bending stiffness due to the presence of failures in rotor blades, which are expected to reduce the bending stiffness.

A list of Key Performance Indicators for the assessment of the condition of rotor blades is given in Table 2. Additionally, the table describes the specifications for the calculation of the KPIs, as well as the typology of sensors required for the measurement.

Table 2: KPIs for monitoring the rotor blades.

KPI	Description	Type of Sensor	Sensor Location
Strain	Measurement of the blade strain for load monitoring and fatigue assessment.	Strain Gauge, FOS	The sensors are frecuently ubicated in the root of rotor blade.
Vibrations	Measure of the natural frequencies, damping and mode shapes as damage indicators.	Accelerometer	The accelerometers are distributed along the rotor blade.
Stress Waves	Diagnosis of the rotor blades based on AE and high frequency analyis.	Acoustic Emission sensors	
Deflection	Measurement of the blade deflection to detect damage in the rotor blades.	Laser-based sensors	The axis of rotation.

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Drones	Evaluate the damage state of rotor blades using drones equipped with high-performance cameras.	Drons equipped with a camera setup and video cameras	Drones can photograph wind turbines from multiple angles and locations.

2.3. SHM of Tower

The fact that the wind turbines are certified for 20 years of operation has been misinterpreted by the end users and the first wind farm business plans were based on the assumption that the blades, towers, foundations, and other structural components were requiring limited or even no maintenance. Nowadays, deformation, vibration, and motion monitoring are commonly used approaches for monitoring the damage state of the tower. The list of Key Performance Indicators considered of interest for the health assessment of towers is shown in Table 3.

Table 3: KPIs for monitoring the tower.

KPI	Description	Type of Sensor	Sensor Location
Strain	Measurement of the tower strains for load monitoring and fatigue assessment.	Strain Gauge, FOS	This type of strain-based sensors are frequently installed in the tower base.
Vibrations	Measure of the natural frequencies, damping and mode shapes as damage indicators.	Accelerometer	The accelerometers are normally distributed at four different levels of the tower.
Inclination	Measure the inclination levels of the towers.	Inclinometer	Biaxial inclinometers (X-Y) can be located at bottom and upper sections of the tower. Alternatively, it can also be located at tower mid-section.
Motions	Movement accross the six Degrees of Freedom of the tower, which are usually defined as surge, sway, heave, roll, pitch, and yaw.	Inertial Measurement Unit (IMU)	The sensors should be located in the bottom and upper sections of the tower.
Thickness	Measurement of the thickness for the assessment of corrosion phenomenon.	Ultrasonic Sensor	Areas with high susceptability to corrosion are Splash Zone and Submerged area of the platform.

Stress Waves	Diagnosis of the cracks, delamination and other internal defects at the early stages using AE and high frequency analysis.	Acoustic Emission sensors	
Drones	Evaluate the damage state of the tower using drones.	Drones are equipped with a camera setup.	Drones can photograph wind turbines from multiple angles and locations without the need of physically enter the blade.

2.4. SHM of Foundations

Foundations for Floating Offshore Wind Turbines can be built in different ways (e.g., spar, tension leg platform, and semisubmersible) depending on the water depth. For example, the monopile fixed foundations are recommended for waters with a depth of fewer than 15 meters, while the jacket foundations are built for waters with a depth of over 30 meters. The list of Key Performance Indicators considered of interest for the health assessment of foundations for fixed wind turbines is shown in Table 4.

Table 4: KPIs for monitoring foundations.

KPI	Description	Type of Sensor	Sensor Location
Strain	Measurement of foundation strains for load monitoring and fatigue assessment.	Strain Gauge, FOS	The strain-based sensors are ubicated in areas with greater susceptibility to damage (hot Spots).
Inclination	The mechanism for the damage detection consist on measure the inclination of foundations.	Inclinometer	
Motions	The system is equipped with a six Degrees of Freedom motion sensor to provide accelerations and gyros of the foundations.	Inertial Measurement Unit (IMU)	The sensor packages should ideally located in opposite corners of the platform.
Thickness	Measurement of the thickness for the assessment of corrosion defects.	Ultrasonic Sensor	The sea water promotes corrosion in Splash Zone, Submerged Zone, etc.

Remote Operating Vehicle	Remote Operating Vehicle are unmanned vehicles equipped with video cameras, lights, sonars, and other tools to carry out underwater inspections.	Remote Operating Vehicles (ROV)	ROV can inspect the foundations, mooring lines, splash zones with a higher level security as compared to swin divers.

2.5. SHM of Floater

The Floater can be defined as a platform with mooring lines that anchor the Floating Offshore Wind Turbine platform on the ground or seabed. The two primary failure modes of the floater of a Floating Offshore Wind Platform are commonly known as fatigue and corrosion.

(a) Fatigue is detected and monitored using strain and vibration-based measurements. A popular approach to estimate the damage accumulation due to fatigue in the structure is the rain flow. For FOWT, it should be pointed out that the floater platform is subjected to periodic impacts of sea waves that lead to damage due to the repetition of cyclic loads.

(b) Typically, the splash zone and the zone below the water level tend to be the most affected zones by corrosion due to the impact of sea waves and the accumulation of stagnant water. Thus, it is highly recommended to include a corrosion protection system for steel-based floaters in Wind Turbine Platform.

A series of relevant Key Performance Indicators for the assessment of the structural health of the floater system are listed in Table 5.

Table 5: KPIs for monitoring floater system.

KPI	Description	Type of Sensor	Sensor Location
Strain	Measurement of the floater strains for load monitoring and fatigue assessment.	Strain Gauge, FOS	The sensor are allocated in the weakest points of the tower (Hot Spots).
Position	The Global Positioning System (GPS) is a satellite-based radio navigation system measures the position of the floater.	GPS system	The GPS system should be installed where it can get a clear view of sky to mantain a reliable reception.
Motions	This system provides six Degrees of Freedom measures to provide accelerations and gyros of the platform.	Inertial Measurement Unit (IMU)	The sensor packages should ideally located in opposite corners of the platform.

Thickness	Measurement of the thickness for the assessment of corrosion phenomenon.	Ultrasonic Sensor	As stated above, Splash Zone, Submerged Zone, etc are sensitive for corrosion failures.
Remote Operating Vehicle	Remote Operating Vehicle are unmanned vehicles equipped with video cameras, lights, sonars, and other tools to carry out underwater inspections.	Remote Operating Vehicles (ROV)	ROV can inspect the foundations, mooring lines, splash zones with a higher level security as compared to swin divers.

2.6. SHM of Mooring Liness

The mooring lines are an essential part of the Floating Offshore Wind Turbines, which can be essentially built with chains, wires, and synthetic fibres. Nowadays, the offshore energy sector has on numerous occasions expressed its concern regarding the high number of accidents due to the failure of mooring lines on floating platforms. The key performance indicators for the monitoring of the mooring lines are detailed in Table 6

Table 6: KPIs for monitoring mooring lines.

KPI	Description	Type of Sensor	Sensor Location
Strain	Measurement of the mooring line strains for load monitoring and fatigue assessment.	Strain Gauge, FOS	The sensors are normally located in Tendons, Chain stopper, Mooring Lines, etc.
Angle of rotation	Estimation of mooring line tension using the values of angular rotations.	Inclinometer	
Position	Measure the global position of the Floating Offshore Wind turbine to detect mooring line failures.	GPS system	
Mooring Tension	Measure the mooring loads of the mooring lines.	Load Cells	Tendons, Chain stopper, Mooring Lines, etc.
Corrosion	Measurement corrosion in mooring lines to assess the condition of the chains (e.g. weight loss measurements, thickness, etc).	Corrosion Sensor	Splash Zone, Submerged Zone, etc.

Remote Operating Vehicle	Remote Operating Vehicle are unmanned vehicles equipped with video cameras, lights, sonars, and other tools to carry out underwater inspections.	Remote Operating Vehicles (ROV)	ROV can inspect the foundations, mooring lines, splash zones with a higher level security as compared to swin divers.

3. LIST OF STANDARDS AND GUIDELINES FOR PREDICTIVE MAINTENANCE OF OWTPs

Table 7 provides a list of relevant classification societies and international standards for the predictive maintenance of FOWT and Tidal Plants. To address this task, it has been addressed standards from reputed classification societies such as Bureau Veritas and Det Norske Veritas along with standards from international organizations such as International Organization for Standardization (ISO), and International Electrotechnical Commission (IEC), among others. The list has been elaborated based on the input from the standardization committee of the FIBREGY project, Bureau Veritas, websites, and end-user experiences. A summary of relevant standards and guidelines for condition motoring considered in the sea trials is detailed in the table below:

Table 7: List of standards and guidelines for predictive maintenance of OWTPs.

Standard	Abbreviation	Description
BV	NI572	NI572 provides specific guidance and recommendations for the classification and certification of floating platforms designed as support of floating offshore wind turbine (FOWT) and is intended to cover floating platforms supporting single or multiple turbines with horizontal or vertical axis.
BV	NI603	NI603 provides requirements applicable to fully submerged current and tidal turbines (CTT) installed on the seabed with a view at their assessment and certification.
DNV	GL-IV-4	Rules and guidelines - IV Industrial Services - Part 4: Guideline for the Certification of Condition Monitoring Systems for Wind Turbines
DNV	RP 0584	RP 0584 provides a comprehensive set of requirements, recommendations, and guidelines for the design, development, operation, and decommissioning of FPV systems.
DNV	SE 0422	SE 0422 specifies services for the certification of floating wind turbines and related components from the floating concept.
DNV	ST 0126	ST 0126 specifies general principles and guidelines for the structural design of wind turbine support structures.
DNV	ST 0164	ST 0164 specifies guidelines for designers, suppliers, and regulators of Tidal Turbines,
IEC	61400-25	Wind Turbines - Part 25: Communications for monitoring and control of wind power plants

ISO	5348	Mechanical vibration and shock - Mechanical mounting of accelerators
ISO	7919-3	Mechanical vibration - Evaluation of machine vibration by measurements on rotating shafts - Part 3: Coupled industrial machines
ISO	10816-1	Evaluation of machine vibrations by measurements on non-rotating parts – General Guidelines
ISO	10816-21	Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts - Part 21: Horizontal axis wind turbines with gearbox
ISO	13372	Condition monitoring and diagnostics of machines — Vocabulary
ISO	13373-1	Condition monitoring and diagnostics of machines - Vibration Condition Monitoring - General procedures
ISO	13373-2	Condition monitoring and diagnostics of machines - Vibration condition monitoring - Part 2: Processing, analysis and presentation of vibration data
ISO	13374	Condition monitoring and diagnostics of machines - Data processing, communication and presentation - Part 1: General guidelines
ISO	13379-1	Condition monitoring and diagnostics of machines - Data interpretation and diagnostics techniques - Part 1: General guidelines
ISO	13379-2	Condition monitoring and diagnostic of machines - Data interpretation and diagnostics techniques - Part 2: Data driven applications
ISO	13381-1	Condition monitoring and diagnostics of machines - Prognostics - Part 1: General guidelines
ISO	16079-1	Condition monitoring and diagnostics of wind turbines - Part 1: General guidelines
ISO	16079-2	Condition monitoring and diagnostics of wind turbines - Part 2: Monitoring the drivetrain
ISO	17359	Condition monitoring and diagnostic of machines - General guidelines

VDI	3834	Measurement and evaluation of the mechanical vibration of wind energy turbines and their components - Onshore wind energy turbines with gears
VDI	3839	Instructions on measuring and interpreting the vibration of machines
VDI	3841	Vibration monitoring of machinery -Necessary Measurements

The regulation NI572 issued by the classification society Bureau Veritas [1] provides guidance notes for the certification of floating offshore wind turbines (FOWT). From this standard, It should be pointed out that the list of items to be monitored for the Floating Offshore Wind Turbine Platforms are as follows:

- drive train, including the gearbox if applicable
- generator
- electrical installations
- safety and control systems
- locking devices and mechanical brakes
- main structural components (hub, nacelle frame, etc.)
- support structure including foundations
- corrosion protection system
- scour protection system, if applicable

According to the standard notes, the frequency recommended for the inspections goes from 3 months up to 5 years depending on the criticality of the component to be inspected in the platform. For example, the inspection of blades, bearings, or shafts should be carried out once a year, however, the composition of the lubricant oils should be analyzed with a frequency of once every semester. In parallel, the NI603 standard [2] provides guidance notes for current and tidal turbines installed on the seabed. From the predictive maintenance point of view, it should be paid special emphasis to appendix 1 "Life Cycle Considerations" which provides guidelines about the type, sampling rate, recurrence, and qualification of the personnel for the inspection of current and tidal turbines.

If we referred to the classification society Det Norske Veritas (DNV), it is worth mentioning Section 9 "In-service inspection, maintenance, and monitoring" of DNVGL-ST-0126 standard [3] which provides guidelines on periodical inspections and monitoring of steel and concrete wind turbine structures. According to this standard, the aspects that should be evaluated during the periodic inspections of the wind turbines are ranked as follows:

- Fatigue cracks
- Deformation
- Buckling
- Control of the tightening torques of the bolts
- Presence of corrosion using Corrosion Protection Systems
- Remove the presence of marine growth (Biofouling)

In parallel, the Chapter 17 of the DNVGL-ST-0164 standard [4] provides minimum requiriments for the corrosion protection systems and condition-based maintenance systems of Tidal Turbines as per example the detection of damage using the resonant frequencies of a certain component.

Similarly, the International Organization for Standardization reported other standards of interest as ISO 7919 "Mechanical Vibration - Evaluation of machine vibration by measurement on rotating shafts" [5], and ISO 10816 "Mechanical Vibration – Evaluation of machine vibration by measurements on non-rotating parts" [6] provides guidelines for inspecting the condition of rotating and non-rotating parts. For such purpose, the standards recommend considering the following aspects:

- Number and distribution of the sensor array.
- Frequency ranges for the detection of faults.
- Data collection and storage
- Data analysis and post-processing

Last, but not least important, it is important to mention Verein Deutscher Ingenieure (VDI) 3834 [7] standard focused on the Measurement and evaluation of the mechanical vibration of wind energy turbines and their components. It should be noted that this standard is specific for the vibration assessment of rotative machinery.

4. DEFINITION OF SHM SYSTEM FOR TOWER OF W2POWER FLOATING OFFSHORE WIND TURBINE

4.1. Description of W2Power FOWT

A schematic picture illustrating a general view of the Floating Offshore Wind Turbine (FOWT) targeted in the project is displayed in Figure 1. From the picture, it is noticed that the FOWT is a bi-turbine platform with up to 12 MW, which will be deployed in the Oceanic Platform of the Canary Islands (PLOCAN) in the Canary Islands in Spain.

Figure 1: Schematic picture of the FOWT targeted in the project.

The 10 m tower has a truncated conical shape with varying diameters and wall thickness along the height. The materials selected for the construction of the FRP-based towers are Zoltek PX35 fibres and SR infugreen 810 resin for a total of 37 layers.

4.2. Description of sensors network of W2Power FOWT

One of the primary objectives of the FIBREGY project is to develop a Structural Health Monitoring system (SHM) to assess the structural integrity of the 1:6 scale FRP-based towers installed in the W2Power Floating Offshore Wind Turbine (FOWT) deployed at the Canary Islands. The SHM system is composed of a network of fibre optic sensors (FOS) embedded in the tower along with strain gauges, accelerometers, gyroscopes, and inclinometers adhered to the tower surface. During the sea trials, the signals of the sensors array are recorded and processed for the evaluation of relevant Key Performance Indicators (KPIs) using Compaq Rio-9054 data acquisition system.

A schematic description of the Structural Health Monitoring to be installed in the tower of the W2Power Floating Offshore Wind Turbine is given in Figure 2, where it can be seen that the tower is divided into four levels which correspond to the green circles marked at 1600 mm, 4000 mm, 7200mm, and 9200 mm height. From the figure, it can be deduced that level 1 at 1600 mm height corresponds to the tower bottom, while level 4 at 9200 mm height is just below the nacelle. Intermediate levels are appreciated at 4000 and 7200 mm height of the tower. Hence, measurements were taken at 4 distinct levels using a total of 2 MEMS (acceleration + gyros), 4 accelerometers, 8 strain gauges, 4 arrays of fibre optic sensors, and 2 bi-axial inclinometers.

Figure 2: SHM of W2Power tower - 4 levels distribution.

The type of signals measured by the monitoring system correspond to accelerations, gyros, strains, temperature, and inclinations, which are recorded and post-processed using a Compact Rio system 9054 supplied by National Instruments. The Compact Rio system is a modular system equipped with the Ni 9205 card for the analysis of acceleration, gyros, and inclinations along with the Ni 923 module specialized for the analysis of strain. In parallel, the SI405 interrogator purchased from HBM will be responsible for the analysis of the strain and temperature signals acquired from the fibre optic sensors network. To ease the handling of data, the data is stored and post-processed by Compaq Rio and SI405 interrogator which has the advantage to be easily accessed through a server.

For the sake of clarification, it is provided a detailed description of the sensor devices part of the Structural Health Monitoring System of the W2Power tower in the sections below.

4.2.1. Acceleration

It is well known that Vibration-based monitoring (VSHM) is one of the most frequent approaches for the detection of faults in the rotative components of wind turbines (e.g. gearboxes, shafts, bearings, etc.). During the sea trials, the signals recorded by the accelerometers at the four levels of the tower provide the time histories of the acceleration data during the sea trials as well as natural frequencies, damping, and mode shapes (bending and torsion modes) of the tower.

The figure reveals that the accelerometers are installed at 4 different levels of the tower which corresponds to 1600 mm, 4000 mm, 7200mm, and 9200 mm as represented in Figure 4. The orientation of the accelerometers installed in the W2Power tower is represented on the right-hand side of Figure 4, where it can be appreciated that the sensors placed at the bottom and top sections of the tower measure the accelerations in the X, Y, and Z axis, while the signals recorded by the sensors allocated in the intermediate positions correspond to X and Y orientations.

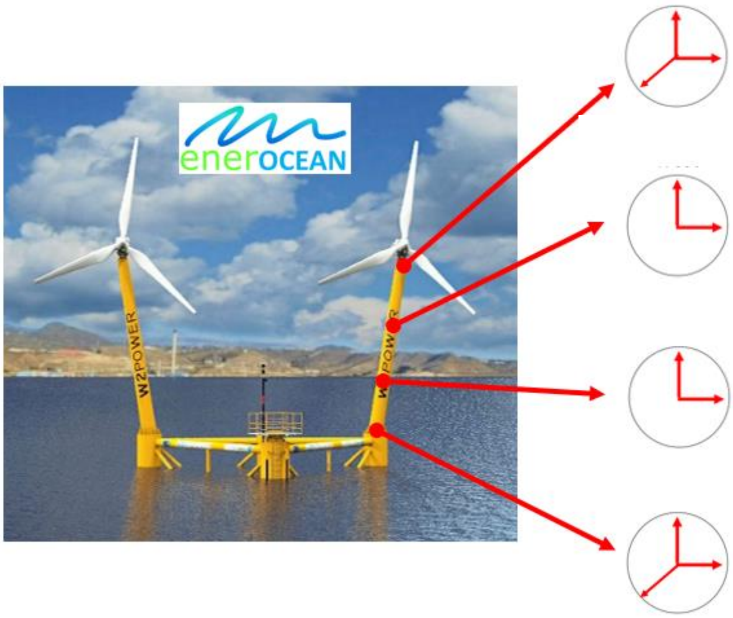


Figure 3: Diagram for the Position and Orientation of accelerometers in W2Power Tower.

Table 9 gives detail about the model of accelerometers used for monitoring the damage state of the tower. On one side, the model of the sensor installed at the top / bottom sides of the tower is "Dytran 7576", which provides the end user X, Y, and Z acceleration (g's) as well rotational information (roll, pitch, yaw expressed in degrees/sec) around those three orthogonal axes. On the other side, the four unidirectional accelerometers "B&K 4381" provides the acceleration signals in the intermediate positions for the X and Y axis. Thus, it can be concluded that the two "Dytran 7576" sensor devices are used to measure the accelerations and gyros in levels 1 and 4 of the tower, while the 4 monoaxial B&K 4381 accelerometers are used to measure the acceleration levels in the intermediate positions (Levels 2 and 3) of the tower.

The values of the ten first natural frequencies of the tower were calculated by the simulation team. The 10 first modes have been simulated by FEM using a Modal Analysis with the software Tdyn Ram Series [9] in the context of WP3. Based on these results, it is obvious that the sensors selected should have high sensitivity in the low-frequency range in order to catch the first bending modes of the tower. To achieve this goal, the Dytran 7573 triaxial accelerometers have a high sensitivity of 470 mV/g in the range of 0-1000 Hz, while the Monoaxial B&K 4381 accelerometers show a nominal sensitivity of 10 pC/m s^2 in the range of frequencies between 0.1 Hz and 4800 Hz.

Table 8: Exact location of the Accelerometers installed in the tower.

	Name	Height (mm)	Angular Position (°)	Measures
Level 1	1 Triaxial Dytran 7576	1600	25	X; Y; Z; roll; pitch; yaw
Level 2	2 Monoaxial B&K 4381	4000		X; Y
Level 3	2 Monoaxial B&K 4381	7200		X; Y
Level 4	1 Triaxial Dytran 7576	9200		X; Y; Z; roll; pitch; yaw

4.2.2. Strain Gauges

It is evident that the strains are of relevant importance for the calculation of stressess in the W2Power tower and therefore, the parts of the tower subjected to higher level of stress needs to be monitored with strain gauges. To carry out this purpose, the strain signals are recorded using eight Strain Gauges supplied by Vishay "CEA-06-250UNA-350" to be installed in the level 1 of the tower (1600 mm) at the angular positions 25°, 115°, 205°, and 295° as it is represented in Table 11. With respect ot the strain gauge installation, It should be pointed out that the strain gauges are installed using a half-bridge configuration, and the angular positions of the four measurement points in the cross section of the tower are shifted 90° from one each other.

Table 9: Exact Position of the strain gauges in the base of the tower.

	Name	Height (mm)	Angular Position (°)	Orientation
Level 1	CEA-06-250UNA-350	1600	25	X, Y
	CEA-06-250UNA-350		115	
	CEA-06-250UNA-350		210	
	CEA-06-250UNA-350		300	

The position and orientation of the strain gauges installed in the W2Power tower are represented on the right-hand side of Figure 4. From the figure, it can be deducted that eight strain gauges are installed at the bottom section of the tower (1600 mm) along the Z-axis of the tower. The main role of the array of strain-based sensors is to enable the identification of the strains and stresses of the tower in the time domain.

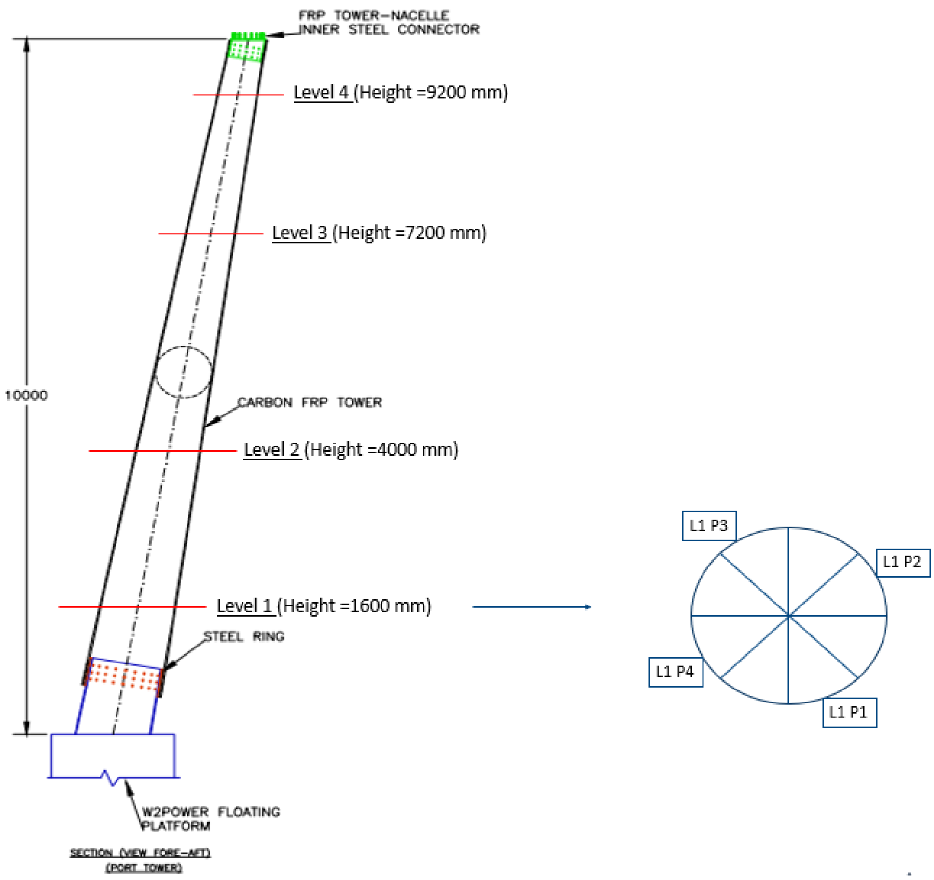


Figure 4: Diagram for the Position of the Strain Gauges in W2Power Tower.

4.2.3. Fibre Optic Sensors

Two approaches – surface-mounted sensors and embedded sensors – described hereafter have been proposed by the FIBREGY consortium for the integration of fibre optic sensors into the W2Power tower.

- Embedded sensors: The sensors are embedded in the interlaminar regions of the tower using hand-lay-up infusion. On the positive side, the integration of the sensors into the FRP materials offers a superior protection level from adverse environmental climate conditions, which is of remarkable interest in the case of wind and tidal energy offshore platforms. On the negative side, the discontinuity generated due to the integration of the sensor can be a precursor of delamination damages with the potential to degrade the structural integrity of the host composite material.
- Surface-mounted sensors: The sensors are commonly mounted on the external parts of the FRP laminar materials using adhesives, studs, or screw connections. The main advantage of this sensor configuration is that it allows ease of access and maintenance for the network of sensors during the operational life of the FOWT.

As mentioned in the document of action, the SHM system will consist of a network of Fibre Optic Sensors (FOS) embedded in the interior of the FRP-based W2Power Tower using the technique of hand-lay-up infusion. This manufacturing option has been selected because of its simplicity for embedding the sensors, however, it is important to ensure that the resin does not cover the FOS connectors during the infusion process in order to guarantee the correct operation of the sensors.

Through the FIBREGY project, the embedding process for the FOS has been carried out by IxBlue shipyards in the framework of WP6, which was responsible for embedding the FOS in the interlaminar regions between the tower and an external layer infused via hand-lay up. Table 12 displays the exact position of the strain-based sensors along the outer perimeter of the tower on Level 1. For this particular case, the signals are recorded using a fiber optical interrogator SI405 supplied by HBM at a sampling frequency rate of 5 Hz. The data of interest are strain in the time domain as well as the maximum, minimum, and average strain/stresses. For the sake of clarification, Figure 5 shows a clear schematic representation of the position of the sensors, where the acronym MP stands for the measurement points 1, 2, 3, and 4.

Table 10: Position of the fibre optic sensors in the tower.

	Name	Height (mm)	Angular Position (°)
Level 1	Measurement Point 1	1600	25
	Measurement Point 2		115
	Measurement Point 3		205
	Measurement Point 4		295

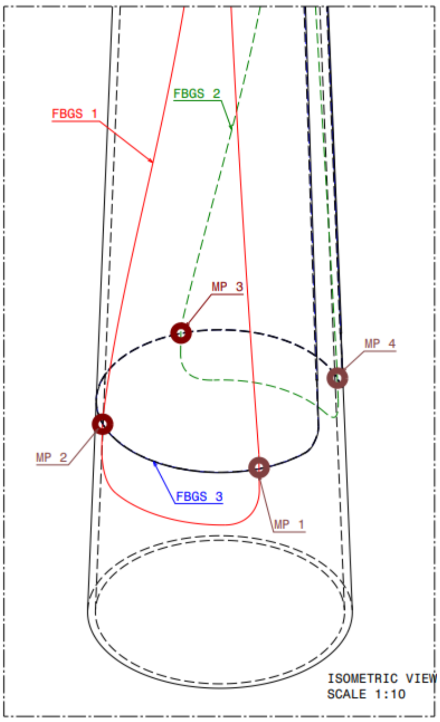


Figure 5: Position of the FOS embedded in the interior of the tower.

On top of that, an array of fibre optic sensors will adhere to the surface of the W2Power tower in the Canary Islands Shipyard (ASTICAN) to measure the shift of temperature in 4 positions of the tower (25°, 115°, 205°, and 295°) at Level 1. The position of the temperature-based sensors is identical to the position of the strain-based sensor as it is highlighted in Table 12, and the only difference is that the temperature sensors need to be attached to the tower's outer surface. In this work, the temperature sensors of the monitoring system play a dual role: 1st) To monitor the temperature variations on the outer surface of the tower in order to gain useful information about the temperature shifts due to sun and shade effects. 2nd) The correction of the strain values due to the influence of the temperature conditions.

4.2.4. Inclinometers

The stability of the W2Power platform is also monitored using an array of two dual-axis DAS-90-A inclinometers which are kindly supplied by Level Developments. The positioning of the inclinometers at the bottom and upper sides of the tower is displayed in Figure 6. From the figure, It can be clearly distinguished that one of the bi-axial inclinometers is placed on the lower side of the tower (Level 1 = 1600 mm), while the other inclinometer is allocated on the upper side of the tower (Level 4 = 9200 mm). The direction of the dual-axis inclinometers can be appreciated on the inset of the right-hand side of Figure 6. The output parameters of interest for the recorded sensor signals are the time histories and the statistical values of the Inclination data.

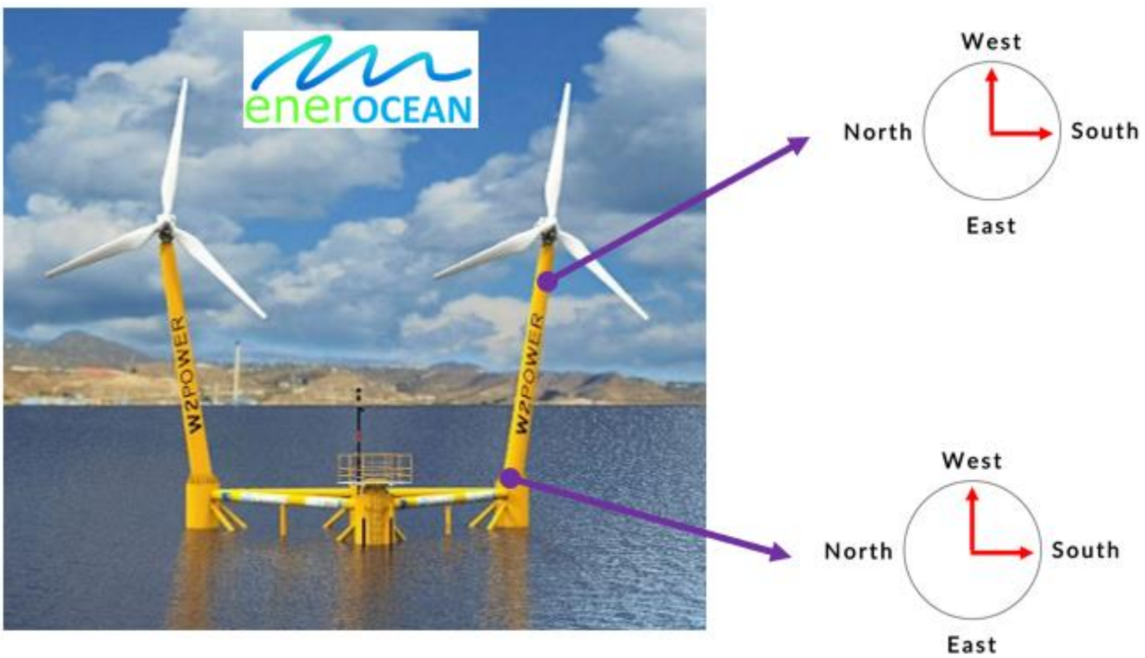


Figure 6: Representation for location of inclination sensors in upper/lower sides of W2Power Tower.

4.2.5. Sea statistics

Environmental loads are referred to the loads caused by wind, waves, current, and other external forces that could induce movements of the W2Power Floating Offshore Wind Turbine platform. For the inspection of the tower, the following parameters will be recorded using an environmental buoy and a meteorological station:

a) Wave height and wave period which are acquired by an environmental buoy.

b) Wind velocity, wind direction, temperature, and humidity, among others. (metereorological station)

The signals acquired by the environmental buoy and meteorological station will be recorded twice daily for 10 minutes, which will provide a global picture of the environmental conditions.

4.2.6. Operating Conditions of Wind Turbine

Supervisory Control and Data Acquisition (SCADA) and a controller (PLC) are widely used by wind operators to control the environmental and operating conditions of Wind Turbines. For this particular work, the data recorded by the SCADA systems: Power, rotor speed, pitch angle, and nacelle direction is recorded to get a deeper understanding of the KPIs. The protocol consists that the signals acquired by the SCADA / PLC system will be recorded twice daily for 10 minutes, which will provide a global picture of the operating conditions of the platform. The main functions of the controller system can be defined as follows:

- Monitoring the enviromental statistics: wind velocity, wind direction, temperature, etc.
- Monitoring the rotational speed of the rotor wind blades.
- Monitoring of the operating mode: manual, automatic, and emergency mode.
- Control of treshold limit values and alarms of the wind turbine.

4.3. Description of Data Acquisition Systems of W2Power FOWT

4.3.1. Compaq Rio

A Compaq Rio data adquisition system has been installed for the inspection and maintenance of the condition of the W2Power Floating Offshore Wind Turbine Platform. The main characteristics of the Compaq Rio can be drawn as follows:

- The model of the Compaq Rio supplied by National Instruments is Ni-cRio-9054, which is a modular system with four slots.
- The Ni9205 is a module with 32 channels that serve for the analysis of the signals recorded by the accelerometers, gyroscopes, and inclinometers.

- The Ni923 is a 4-channel module focused on the analysis of the signals acquired by the network of strain gauges.
- LabVIEW is a programming language developed by National Instruments used for the configuration of Ni-cRio-9054 software.

The Compaq Rio Data Acquisition System will play a pivotal role in the SHM system: 1st) The cRio-9054 is used as a data acquisition system for the signals recorded by the accelerometers, gyroscopes, inclinometers, and strain gauges. 2nd) The data recorded by the cRio-9054 system is post-processed for the calculation of relevant Key Performance Indicators for the assessment of the damage status of the tower.

For the sake of clarification, the data analysis via C-Rio Data Acquisition System (DAS) can be categorized into three consecutive steps:

1) Data acquisition: The raw data of the sensors (e.g. vibration amplitude in the time domain) will be recorded for periods of 10 minutes twice a day. The sampling frequency rate used for recording statistical data and FFT spectrums with the MEMS and accelerometers is 1000 Hz. However, it should be emphasized that the recorded time series will be re-sampled with a sampling frequency of 20 Hz to reduce the amount of data shared by the communication system. With regards to the Strain Gauges and Inclinometers installed in the platform, the sampling frequency rate used will be 100 Hz and 1 Hz, respectively.

   The Sea Test Trials will be held in the test site of the Oceanic Platform of the Canary Islands (PLOCAN), which is held in the Canary Islands.

2) Data processing: The large amount of data collected in the sea trials will be processed to obtain relevant key performance indicators (KPIs) which will inform about the structural condition of the tower.

3) Interpretation of the data: A diagnostic step is required to investigate the trend of the data with the purpose to get valuable information about the detection, quantification, and location of defects in the platform. Having identified the existence of a fault, the following step aims at estimating how soon and how likely failure will occur (Prognosis of the remaining useful life).

4.3.2. SI405 Interrogator

The SI405 interrogator purchased from HBM has been selected for the analysis of the strain and temperature signals acquired from the fibre optic sensors network. As explained in Section 4.2.3, the strain-based fibre optic sensors have been embedded in the tower by hand-lay up infusion, while the temperature-based sensors are attached to the surface. The main characteristics and functions of the SI405 interrogators are drawn below:

- The model of the Interrogator supplied by HBM is SI405.
- The sampling frequency rate for the data acquisition is 5 Hz.

- The number of channels used in the interrogator is 3 for the strain signals and 1 for temperature signals.
- The output parameters of interest are the deformation and stress data in the time domain.
- The stadistical parameters of interest are the maximum, minimum, average, and standard deviation.

4.3.3. SCADA system

The Key Performance Indicators are strongly influenced by the local environmental and operating conditions of the W2Power Wind Turbine platform. For example, the results given in [10] show that the variation in wind speed and operation conditions of the platform leads to a drastic variation in the measured raw data. Thus, it is of vital importance to investigate the relationship between the key performance indicators and the environmental / operating scenario of the turbine.

Supervisory Control and Data Acquisition (SCADA) is a computer-based system for gathering and analyzing real-time data to monitor the performance of the turbine. The minimum data set type recorded for the SCADA system includes 10 minutes average values of power, rotor speed, pitch angle, and nacelle direction at a frequency rate of 1 Hz.

4.4. Description of the Communication System of W2Power FOWT

The W2Power Platform is deployed in the Oceanic Platform of the Canary Islands (PLOCAN) testing site area which is located a few meters from shore. To ease the handle of data, the data stored and post-processed by both Compaq Rio and SI405 interrogator can be easily accesed through a server. For this particular case scenario, two configurations of data transmission systems are recommended:

(i) Ethernet data transmission through a cable.

(ii) Wifi data transmission through a wireless conection.

A comparison between the pros and cons of both data transmission systems is presented in the framework of Table 13. The table reveals that the Ethernet connection presents a maximum data transmission speed of 10 Gbps as compared to 2.4 Gbps of WiFI wireless connection. As a general rule, the transmission of files between two computers is faster through an Ethernet connection because the cable is not affected by the obstacles in the transmission path. Thus, Ethernet will result in a better connection in terms of reliability and security for data transmission as compared to WiFI wireless transmission systems.

In telecommunications, Latency can be defined as the delay caused by data traffic traveling from a device to its destination, and it is associated with the number of obstacles presented in the signal´s way. It is evident that the Wi-FI wireless connection is subjected to numerous physical obstacles for example walls or furniture blocking your data transmission path and therefore, it provides less latency than Ethernet cables. If we look at cyber security, ethernet cables are more secure than Wi-Fi wireless connection because can be accessed by physical terminals of the network, while Wi-Fi connections can be intercepted by other uses as it travels through the air.

Another aspect of importance is data transmission for both communication systems. For instance, an ethernet cable is designed to work at a maximum distance of 100 meters without degration of speed and latency. On the contrary, Wi-Fi signals can reach over 15 meters for a 5 Ghz frequency and 45 meters for a 2.4 Ghz frequency. Hence, it is evident that the Wi-FI wireless connection has a less range of transmission than the ethernet cables. As a general conclusion, it is noticed that the ethernet connection ennables the transmission of high-volumen of data and it is highly recommended for the transmission of data in ranges of short distances.

Table 11: Ethernet and Wi-Fi wireless connection comparison.

	Ethernet cable	Wi-FI wireless connection
Maximum Speeds	10 Gbps	2.4 Gbps
Latency	10 ms	50 ms
Ciber-security	More Secure	Less secure
Range	100 m	15 - 45 m

It is well known that there is a large number of systems that could be used for the communication system of the W2Power W2Power Wind Turbine such as for example communication WiMAX, LoRaWAN, and via Satellite.

- For a short distance scenario (less than 50 metres), the Ethernet connexion enables the transmission of large volume of data with wired connections, while WiFi connexion enables the transmission of large volume of data whitin a distance of 70 metres. Whenever it is possible, as compared to WiFi configurations, the use of Ethernet connections is recommended due to their higher capacity, security, and realibility.
- For a mid distance scenario, the Worldwide Interoperability for Microwave Access (WiMAX) is a wireless broadband communication standards, which can be used for distances of up to 30 Km. In parallel, LoRaWAN is a communication protocol to enable the comunication for long distances of 20 km. For such a case, the WiMAX networks are highly recommended due to multiple factors such as higher connectivity range and transmission speeds.
- For a far distance scenario (greater than 30 km), the use of artificial satellites can be used to provide communication links between various points on Earth with latency speeds of 550 ms.

The FOWT platform is located near the sea coast in PLOCAN testing site, and therefore the data transmission of the SHM system will be executed through a WiMAX (with the possibility for 3G/4G backup), which is a communication system capable to provide robust communications in the harsh sea environment without losing relevant information during the data transmission. The data generated during the sea trials will be shared securely following a specific communication protocol.

4.5. Description of the IP rating

The array of sensors, connectors, and the monitoring cabinet installed in the W2Power platform should fullfill a series of protection requirements to ensure operation in the agressive sea conditions. If we look at the W2Power platform, the two most conditioning aspects when selecting the equipment are to be located in a marine environment with possibility of water ingress. Other conditioning aspects are high temperatures, electromagnetic interferences or possibility for electrical signal losses due the cable distances.

First Digit Number	Protection provided against solids	Second Digit Number	Protection provided against liquids
0	No protection	0	No protection
1	Protection against objects > 50 mm (e.g. bird strike)	1	Protection against vertically dripping water
2	Protection against objects > 12.5 mm (e.g. fingers)	2	Protection against angled dripping water
3	Protection against objects > 2.5 mm (e.g. hailstone)	3	Protection against sprayed water.
4	Protection against objects > 1.0 mm (e.g. wires)	4	Protection against splashed water.
5	Partial protection against dust	5	Protection against low pressure water jets.
6	Full protection against dust	6	Protection against high pressure water jets.
		7	Protection against the effects of immersion at a depth of 1 m.
		8	Protection against the effects of immersion for a long time period

Table 12: Ingress Protection Rating to define Level of protection for solids and liquids [11]

It is well known that the electrical systems of sensors and data acquisition systems can be damaged because of the penetration of solid and liquid particles. The factor considered for the protection of sensors and acquisition systems to be installed in the W2Power towers is the IP scale, which defines how well the sensors will be protected from contact with dust and water [11]. The code of the IP scale consists of two numbers, which are provided as follows: IP-XX to provide the levels of protection required against solids and liquids defined in the IP Rating (see Table 14).

- The first digit number designates the level of protection of the sensors against solid objects on a scale of 0 (no protection) to 6 (dust-tight protection);
- The second number designates the device's protection against liquids, where the minimum level of protection is referred to as 0 (no protection) and the maximum level of protection stands for 8 (protection against long periods of immersion).

Consequently, the Ingress Protection Rating required depends on the conditions of the environment where the sensors and data acquisition system are installed. For example, the sensors installed in the nacelle require a degree of protection (IP63 or IP64), whereas equipment installed in a submerged area of the W2Power platform require a protection level of IP68. The IP protection ratings of the equipment installed on the W2Power platform are as follows:

- Monitoring Closet (IP = 67)
- Compact-Rio (installed in monitoring cabinet)
- Interrogator (installed in monitoring cabinet)
- MEMS
- Accelerometers UD
- Strain Gauges
- Inclinometer
- Cables (The cables will be protected with corrugated pipes to avoid corrosion failures)

It should be outlined that the MEMS, Accelerometers UD, Strain Gauges, and Inclinometers will be protected from the aggressive sea conditions using special coatings, and special protections in order to minimize the harshness of the aggressive marine conditions.

4.6. Description of the Monitoring Cabinet

The SHM system installed in the W2Power is composed of the following components:

- Data Adquisition Systems (C-Rio 9040 and Interrogator SI405)
- Sensor network (MEMS, accelerometer, Strain Gauge, Fibre Optic Sensors, among others)
- Communication Network (Ethernet connection)

The sensor network convert physical parameters such as acceleration, velocity, deformation, etc. into electric signals which are recorded and post processed for Data Adquisition Systems. Subsequently, 80 Megabytes of valuable data are transmitted from the Compaq Rio to the Virtual Machine a day for further analysis.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

Monitoring cabinets are a key element in a monitoring system with a dual role: On one hand, the protection of Data Acquisition Systems from the aggressive external environmental conditions of the sea (humidity, temperature, etc.), and on the second hand, data collection and recording of the signals provided by the sensor array. In general, the main components of a monitoring cabinet can be drawn as follows:

- Monitoring Cabinet: The Data Acquisition systems and electronic devices are placed in the monitoring cabinets with the aim to protect both equipment from external risks such as temperature, humidity, and vibrations, among others with the purpose to extend their service life.
- Data Acquisition Systems is a computer-based information system for collection, processing, and analysis of the information. During the sea trials, C-Rio 9040 processes the signals acquired for the MEMS, accelerometers, inclinometer and Strain Gauges, while the Interrogator processes the signals acquired for the four arrays of Fibre Optic Sensors.
- Power Supply serves to convert voltage current (AC) into direct current (DC) to power the electronic instrumentation of the monitoring cabinet with the required voltage, current, and frequency.
- Magnetothermic is an automatic switch with the function of protecting the electronic devices in case of short circuits, overvoltages as well as malfunction of electronic equipment.
- Terminals and connectors will be used for the connection of wires and cables with signal aconditionators, interrogators, and data acquisition system in the monitoring cabinet.
- Galvanic isolators have the function of preventing the appearance of unwanted current flows in electrical systems which are useful for protection of overvoltages and corrosion failures.
- Cables: During the sea trials, the wires will be protected from the external environment with corrugated pipes to minimize the corrosion generated from the high levels of humidity and salinity in the sea.
- Cable Channel: The cables are guided with cable channels in the interior of the monitoring cabinet as it is shown in Figure 7.
- DIN Rails: A DIN rail is a metal rail designed for attaching electrical devices such as power supplies, galvanic isolators, data acquisition systems, terminals, connectors, etc. There are three DIN Rails in the monitoring cabinet installed for the inspection and maintenance of the W2Power FOWT.

For the sake of clarification, Figure 7 provides an example of the electronic instrumentation part of a monitoring cabinet. To avoid breakage of the electronic equipment, it is highly recommended that the monitoring cabinets are well protected from heat through a cooling system and external protection coatings. Similarly, the penetration of undesirable solids and liquids in the monitoring cabinet shall be avoided by using an appropiate Ingress Protection Rating in the monitoring cabinet.

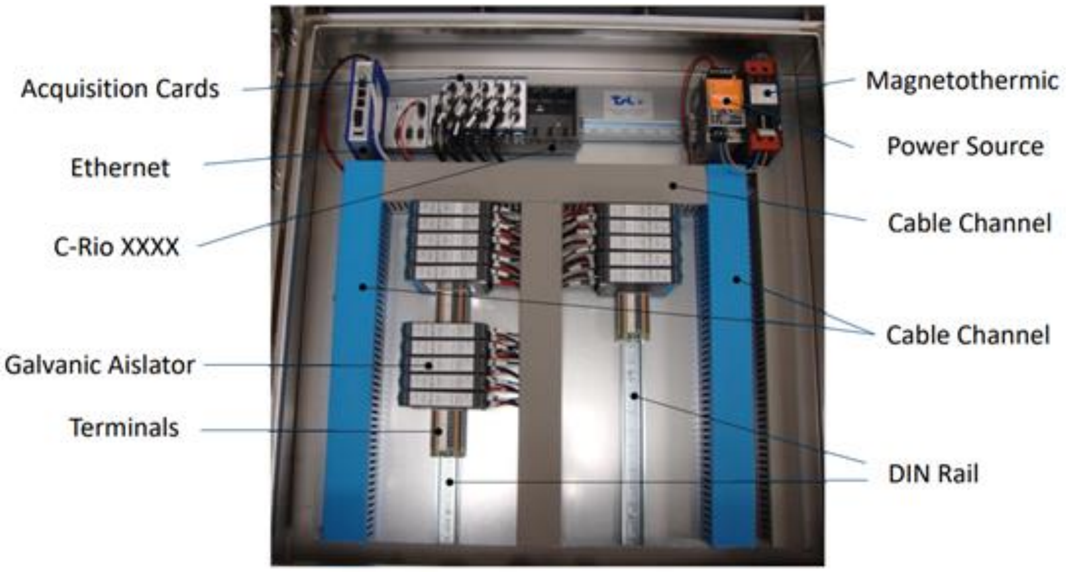


Figure 7: Components of a Monitoring Cabinet [12].

Figure 8 represents a diagram with the connections between the Data Acquisition System (C-Rio 9040 - Ni 9205 and Ni 9237) and the sensors distributed in the strategic positions of the W2Power wind turbine platform.

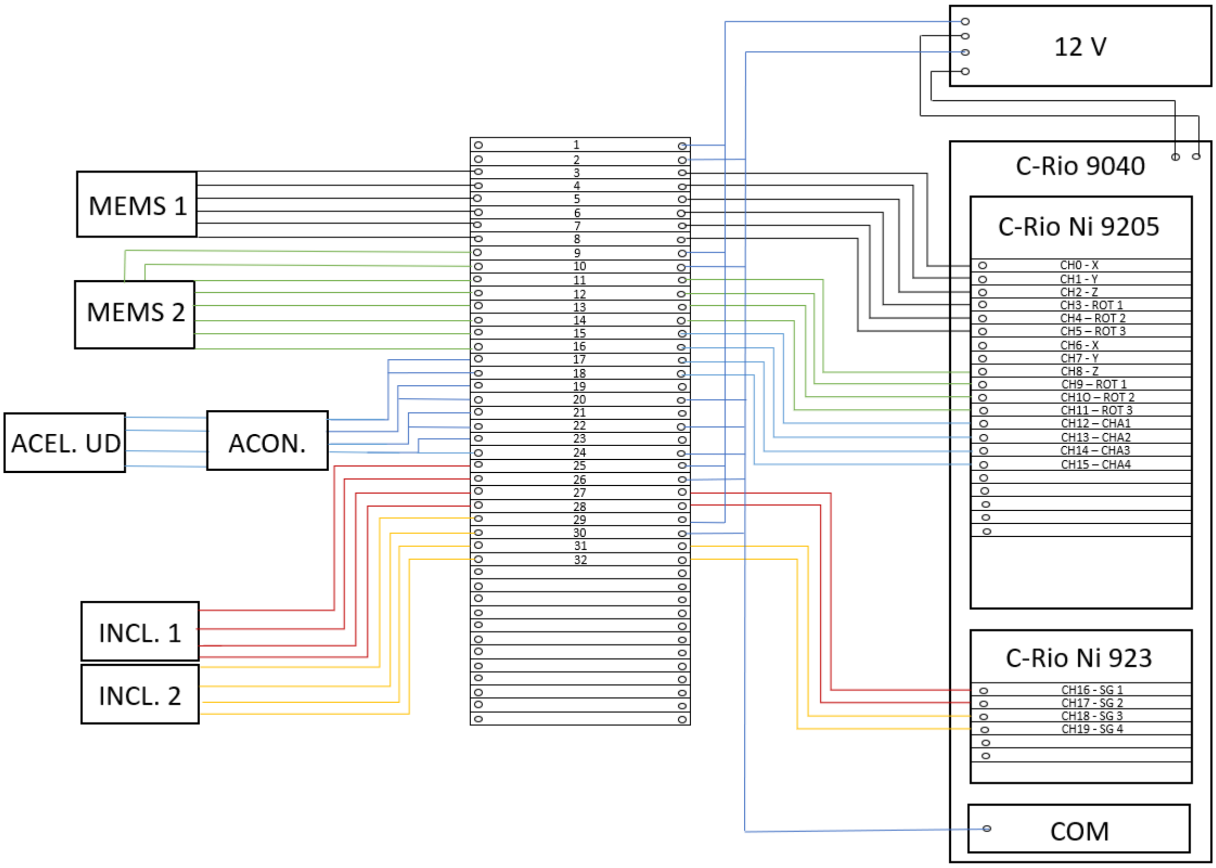


Figure 8: Diagram showing the connections between the DAS and the sensors.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

5. DAMAGE INDICATORS

The damage indicators are referred to as the Key Performance Indicators (KPIs) analyzed during the sea trials as it is detailed in the paragraphs below:

- Acceleration data: Vibration-based monitoring is widely used for the inspection of the condition of rotative machinery such as shafts, bearings, and high-speed shaft, among others. The main idea behind this analysis is to investigate the trend of the evolution of acceleration data in a time period and the detection of vibration patterns that fall outside the range exhibited by a reference pattern.
- Displacements: The double integration of the acceleration data is used to calculate the platform displacements of the platform. For example, the report will investigate the relationship between the significant wave height (m) and the displacements (mm) of the platform in order to have a clear idea about the condition of the platform.
- Motions: The motion tracking system provides real-time monitoring of the global motions of the platform (e.g., heave, roll, pitch, surge, yaw, and sway). These indicators are useful information that provide relevant information about how the energy of the sea translates into the motion of the FOWT platform.
- Natural frequencies: By monitoring the natural frequencies of a structure, the SHM system can identify relevant structural damages such as scouring, brace failure, or mooring lines failures. During the sea trials, the ten first modes of the platform are monitored several times a day using an array of MEMS and accelerometers installed in strategic points. This information can be useful to extend the service life of the structure due to the significant reduction of the time that the structure remains in a weakened state.
- Mode shapes: A mode shape provides a visual representation of the deformation of the FOWT when vibrating at one of the resonant natural frequencies. The mode shapes provide valuable information for at least two reasons: 1st) the displacement of the mode shapes determines the parts of the structure that should be reinforced from the dynamic point of view and 2nd) the curves of the mode shapes are strongly affected by the presence of delamination defects and local failures [13]. A relevant parameter proposed for the detection of damage in FOWT is the shift of the mode shapes due to stiffness reduction which produces changes in the curvature of the modes.
- Deformation: The deformation and stress levels of the platform will be controlled using an array of strain gauges and Fibre Optic Sensors installed with a half-bridge configuration. The strain gauges are frequently installed in hot spots such as transition pieces, the root of rotor blades, and the tower base, among others. The tracked deformation levels will be represented in the time domain in periods of 10 minutes a day, which will be used to calculate mean, standard deviation, maximum and minimum values.
- Inclination: Inclinometers are frequently used to monitor the lateral movements of the platform as well as control of the stability of the platform and mooring line tensions. The angular measurements are either given an angular measurement (e.g. degrees, minutes, and seconds) or as a percentage

with reference to a level zero plane. The measurements of the inclinometers can be used to calculate the Flexural and torsional tower moments for various sea scenarios by Mohr's theorem.

- Sea statistics: The crash of the sea waves is responsable for operation downtimes of offshore structures and therefore, it should be controlled and monitored using a meteorological station and/or environmental buoy. The sea statistics will be recorded during the sea trials with the aim to obtain the wave height, wave period, wind velocity, wind direction, humidity, etc and their correlation with the damage indicators. This information will be included in the measurement report (D6.6).
- Operational conditions: The operation conditions of the platform are monitored by the SCADA and PLC system of the platform, which provides relevant parameters of interest such as power, rotor speed, pitch angle, or nacelle direction. The data gathered in the deliverable 6.6 will be classified as a function of the both sea statistics and operation conditions.

It is widely known that Corrosion is a limiting factor of the service life of FOWT and Tidal plants, which will be of special relevance for the steel-based components of the atmospheric and splash zone of the W2Power FOWT platform. Therefore, it is evident that the metallic components of the turbine shall be protected from the corrosion using corrosion protection systems. However, this phenomenon has not been considered for the FRP-based tower which is not expected to be affected by corrosion due to the material selection.

The regular impact of the sea waves in the FOWT is fatigue loads that should be considered in the design assumptions. These types of loads are used to predict the residual life of the FOWT using fatigue models and advanced algorithms, which are currently in the development stage. The measurement report does not consider fatigue because the time required to perform the different fatigue tests is greater than the 3-5 months of duration of the sea trials, however, this phenomenon should be considered for further research in future research and development projects.

6. CONCLUSIONS

The Structural Health Monitoring system integrated into the tower of the W2Power Floating Offshore Wind Turbine has the fundamental purpose to provide relevant information about the tower's structural integrity with the aim to increase its lifetime and avoid unforeseen downtimes. The main outcomes of this deliverable are summarized below:

- Based on an extensive literature review, a set of relevant Key Performance Indicators for inspection and monitoring of the mooring lines, foundations, tower, rotor blades, and drivetrain of the FOWTs have been offered. According to the SHM community, the relevant Key Performance Indicators for the analysis of the structural integrity of a tower are Strain, Stress, Vibration, Inclination, Motion, Thickness, and visual images captured from multiple angles and locations.
- Apart from that, the deliverable presents a list of relevant guidelines and classification society standards focused on the predictive maintenance of FOWT and Tidal Plants. If we look at the frequency of the inspections, the frequency of inspections varies in the range from real-time up to 5 years depending on the criticality of the component to be inspected. With regards to the typical failure modes, the standard states that the aspects that shall be evaluated during the periodic inspections of FOWT and Tidal Plants are shortlisted as deformation, buckling, corrosion, and fatigue cracks, among others.
- Another aspect addressed in D.4.8 is the definition of the SHM system installed for regular inspection and maintenance of W2Power Floating Offshore Wind Turbine. The SHM system is composed of a network of MEMS, accelerometers, strain gauges, fibre optic sensors, and inclinometers along with a meteorological station for assessment of sea environmental loads. A data set of 10 minutes (twice a day) is processed through Compaq Rio 9054 data acquisition system and an HBM SI405 interrogator with the purpose to obtain relevant Performance Indicators (e.g. displacements, deformation, frequencies, etc.) and statistical values which are transmitted to an external server.
- Last, but not least important, a diagram with the wire connections between the Compaq Rio 9054 and the sensor network is offered in the context of the deliverable. Similarly, a detailed description of the multiple components of the monitoring cabinet used for the sea trials is offered.

In conclusion, this work lays the foundations of the Structural Health Monitoring system developed for the monitoring of the structural health of the Tower of the W2Power FOWT in the framework of the FIBREGY project. The finding of this report can have important applications for monitoring the condition of structural components of energy renewable platforms such as FOWT and Tidal plants targeted in the project.

7. RECOMMENDATIONS AND FUTURE WORK

Even though the research on this topic started more than ten years ago and a solid knowledge on the topic has been built since them. There are several research gaps in the literature that still need to be addressed and some of them are indicated in the bullet points below.

- Determinate the loads due to waves and currents in offshore wind turbine structures.
- Development of AI/ML approaches for automatic classification of damages.
- Development of digital twins for virtual sensing of offshore wind turbines.
- Development of innovative monitoring approaches for wind turbines (e.g., inspection of mooring lines using GPS systems, etc.)

The number of offshore wind structures increases day after day and a substantial number of these engineering structures are reaching the end of their life, which is proof of the need to develop advanced SHM systems for the life extension of these structures. The data generated by the SHM system of the W2Power FOWT will be used for multiple purposes:

- Calculation of relevant Key Performance Indicators of the structure – displacement response to wave loading, natural frequencies, motions, etc.
- Identification of the thresholds and alarms for multiple sea scenarios.
- Extend the life of structures reaching their original design life.
- Investigation of the relationship between metoceanic conditions and key performance indicators.
- Feed the digital twin models developed within the project with experimental data.
- Validation and verification of the numerical models.

8. APPENDIX - CERTIFICATES OF CALIBRATION

8.1. MEMS

7576 A1

DYTRAN INSTRUMENTS, INC.

Dytran Instruments, Inc.
21592 Marilla St. Chatsworth, CA 91311 Ph: 818-700-7818
Fax 818-698-0362, www.dytran.com email: info@dytran.com

ilac-MRA | A2LA ACCREDITED

CALIBRATION CERTIFICATE

CUSTOMER:	*RIVAS INGENIERIA S.L.*		**STATION:** 6	**REPORT #:** 416	
PO #:	*RIV_2023_14.0*	**SO#:** *223319*	**TEMP (°C):** 24	**PROCEDURE:** TP-3002	
MODEL:	*7556A2*	**S/N:** *416*	**TYPE[1]:** 1	**AS RECEIVED:**	**AS RETURNED:**

INPUT	FREQUENCY	ACCEL X	ACCEL Y	ACCEL Z	GYRO X	GYRO Y	GYRO Z
g's	Hz	mV/g	mV/g	mV/g	(mV/°/s)	(mV/°/s)	(mV/°/s)
1.00	20	208.82	211.65	205.97	1.09	1.04	1.01
1.00	30	208.75	211.92	206.05	(BIAS VDC)	(BIAS VDC)	(BIAS VDC)
1.00	50	211.15	213.33	207.15	2.51	2.50	2.47
1.00	**100**	**208.79**	**212.16**	**206.05**			
1.00	300	202.86	205.97	199.06			
1.00	500	193.68	196.01	186.57			
1.00	1000	159.91	163.26	143.82			
BIAS	VDC	2.51	2.48	2.52			

CALIBRATION EQUIPMENT		
DII#	**DESCRIPTION**	**CAL. DUE DATE**
1656	DAQ	4/27/2023
1868	ACCELEROMETER	4/19/2023
2068	USB DAQ	6/3/2023

CALIBRATION NOTES:

- [1] CALIBRATION TYPE CODE:
  1 NEW UNIT 2 RE-CALIBRATION
- [2] IF APPLICABLE
- [3] UNCERTAINTY STATEMENT APPLIES TO CALIBRATED PARAMETERS ONLY
- [4] THIS CALIBRATION WAS PERFORMED IN ACCORDANCE WITH ANSI/NCSL Z540-1-1994, ISO 10012-1, ISO/IEC17025, AND TRACEABLE TO NIST
- [5] IN CASE OF IEPE SENSOR THE CALIBRATION IS PERFORMED USING 24 VDC COMPLIANCE VOLTAGE LIMITED TO 5 mA OF CURRENT
- [6] COMPLIANCE JUDGEMENT IS MADE ON READINGS. UNCERTAINTY OF CALIBRATION IS NOT TAKEN INTO ACCOUNT

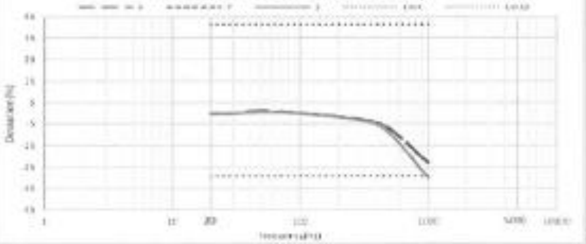
- AS RECEIVED/AS RETURN CODES
  1 = IN TOLERANCE, NO ADJUSTMENTS; 2 = IN TOLERANCE, BUT ADJUSTED
  3 = OUT OF TOLERANCE < 5%; 4 = OUT OF TOLERANCE > 5%
  5 = REPAIR REQUIRED; 6 = REPAIRED AND CALIBRATED
  7 = UNIT NON-REPAIRABLE, RECOMMEND REPLACEMENT
  8 = UNIT SERVICEABLE WITH CURRENT CALIBRATION DATA

- ESTIMATED UNCERTAINTY OF CALIBRATION [3]
  SENSITIVITY OVER FREQUENCY: [illegible]
  SENSITIVITY AT TEMPERATURE: [illegible]
  TRANSVERSE SENSITIVITY: [illegible]
  ACOUSTIC PRESSURE: [illegible]
  STATIC FORCE: [illegible]
  DEAD WEIGHT: 0.7%
  DROP SHOCK: [illegible]
  STATIC PRESSURE: [illegible]
  IMPULSE FORCE: [illegible]
  LINEARITY: [illegible]
  DC VOLTAGE: [illegible]
  COVERAGE FACTOR k=2 CONFIDENCE LEVEL 95%
  SINGLE ENDED MEMS UNIT: [illegible]
  ACCREDITATION CALIBRATION IS ONLY FOR PARAMETERS WHICH ARE STATED FOR

- THIS CERTIFICATE SHALL NOT BE REPRODUCED EXCEPT IN FULL, WITHOUT THE WRITTEN PERMISSION FROM DYTRAN INSTRUMENTS, INC. DATA RESULTS RELATE ONLY TO THE MODEL AND SERIAL PRESENTED ON THE CERTIFICATE. LIMITATION OF USE: IN ACCORDANCE WITH PERFORMANCE SPECIFICATION OF CALIBRATED MODEL

Cal. Tech:	DEREK MONTES
ISSUE DATE:	*2/3/2023*
TEST DATE:	*2/3/2023*

FREQUENCY RESPONSE (IF APPLICABLE)



-----END OF REPORT-----

7556 A2

Dytran Instruments, Inc.
21592 Marilla St. Chatsworth, CA 91311 Ph: 818-700-7818
Fax 818-698-0362, www.dytran.com email: info@dytran.com

CALIBRATION CERTIFICATE

CUSTOMER:	RIVAS INGENIERIA S.L.	STATION:	6	REPORT #:	416
PO #: RIV_2023_14.0	SO#: 223319	TEMP (°C):	24	PROCEDURE:	TP-3002
MODEL: 7556A2	S/N: 416	TYPE[1]:	1	AS RECEIVED:	AS RETURNED:

INPUT	FREQUENCY	ACCEL X	ACCEL Y	ACCEL Z	GYRO X	GYRO Y	GYRO Z
g's	Hz	mV/g	mV/g	mV/g	(mV/°/s)	(mV/°/s)	(mV/°/s)
1.00	20	208.62	211.65	205.97	1.09	1.04	1.01
1.00	30	208.75	211.92	206.05	(BIAS VDC)	(BIAS VDC)	(BIAS VDC)
1.00	50	211.15	213.33	207.15	2.51	2.50	2.47
1.00	100	208.79	212.16	206.05			
1.00	300	202.86	205.97	199.06			
1.00	500	193.68	196.01	186.57			
1.00	1000	159.91	163.26	143.82			
BIAS	VDC	2.51	2.48	2.52			

CALIBRATION EQUIPMENT		
DB#	DESCRIPTION	CAL. DUE DATE
1656	DAQ	4/27/2023
1868	ACCELEROMETER	4/19/2023
2068	USB DAQ	6/3/2023

CALIBRATION NOTES:

- [1] CALIBRATION TYPE CODE:
1-NEW UNIT 2-RE-CALIBRATION
- [2] IF APPLICABLE
- [3] UNCERTAINTY STATEMENT APPLIES TO CALIBRATED PARAMETERS ONLY
- [4] THIS CALIBRATION WAS PERFORMED IN ACCORDANCE WITH ANSI/NCSL Z540-1-1994, ISO 10012-1, ISO/IEC17025, AND TRACEABLE TO NIST
- [5] IN CASE OF IEPE SENSOR THE CALIBRATION IS PERFORMED USING 24 VDC COMPLIANCE VOLTAGE LIMITED TO 5 mA OF CURRENT
- [6] COMPLIANCE JUDGEMENT IS MADE ON READINGS. UNCERTAINTY OF CALIBRATION IS NOT TAKEN INTO ACCOUNT.

- AS RECEIVED/AS RETURN CODES:

1 = IN TOLERANCE, NO ADJUSTMENTS | 2 = IN TOLERANCE, BUT ADJUSTED
3 = OUT OF TOLERANCE < 5% | 4 = OUT OF TOLERANCE > 5%
5 = REPAIR REQUIRED | 6 = REPAIRED AND CALIBRATED
7 = UNIT NON-REPAIRABLE, RECOMMEND REPLACEMENT
8 = UNIT SERVICEABLE WITH CURRENT CALIBRATION DATA

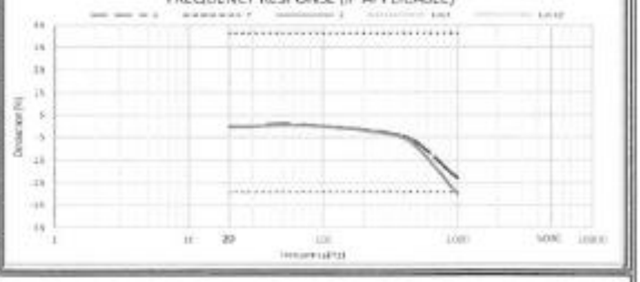
- ESTIMATED UNCERTAINTY OF CALIBRATION[3]:

SENSITIVITY OVER FREQUENCY: [illegible]
SENSITIVITY AT TEMPERATURE: [illegible]
TRANSVERSE SENSITIVITY: [illegible]
ACOUSTIC PRESSURE: [illegible]
STATIC FORCE: [illegible]
DEAD WEIGHT: 0.7%
DROP SHOCK: [illegible]
STATIC PRESSURE: [illegible]
IMPULSE FORCE: [illegible]
LINEARITY: [illegible]
DC VOLTAGE: [illegible]
COVERAGE FACTOR k=2, CONFIDENCE LEVEL 95%
SINGLE ENDED MEMS UNIT: [illegible]
*ACCREDITATION CALIBRATION IS ONLY FOR PARAMETERS WHICH ARE STATED FOR

- THIS CERTIFICATE SHALL NOT BE REPRODUCED EXCEPT IN FULL, WITHOUT THE WRITTEN PERMISSION FROM DYTRAN INSTRUMENTS, INC. *DATA RESULTS RELATE ONLY TO THE MODEL AND SERIAL PRESENTED ON THE CERTIFICATE *LIMITATION OF USE: IN ACCORDANCE WITH PERFORMANCE SPECIFICATION OF CALIBRATED MODEL.

Cal. Tech:	DEREK MONTES
ISSUE DATE:	2/3/2023
TEST DATE:	2/3/2023

FREQUENCY RESPONSE (IF APPLICABLE)

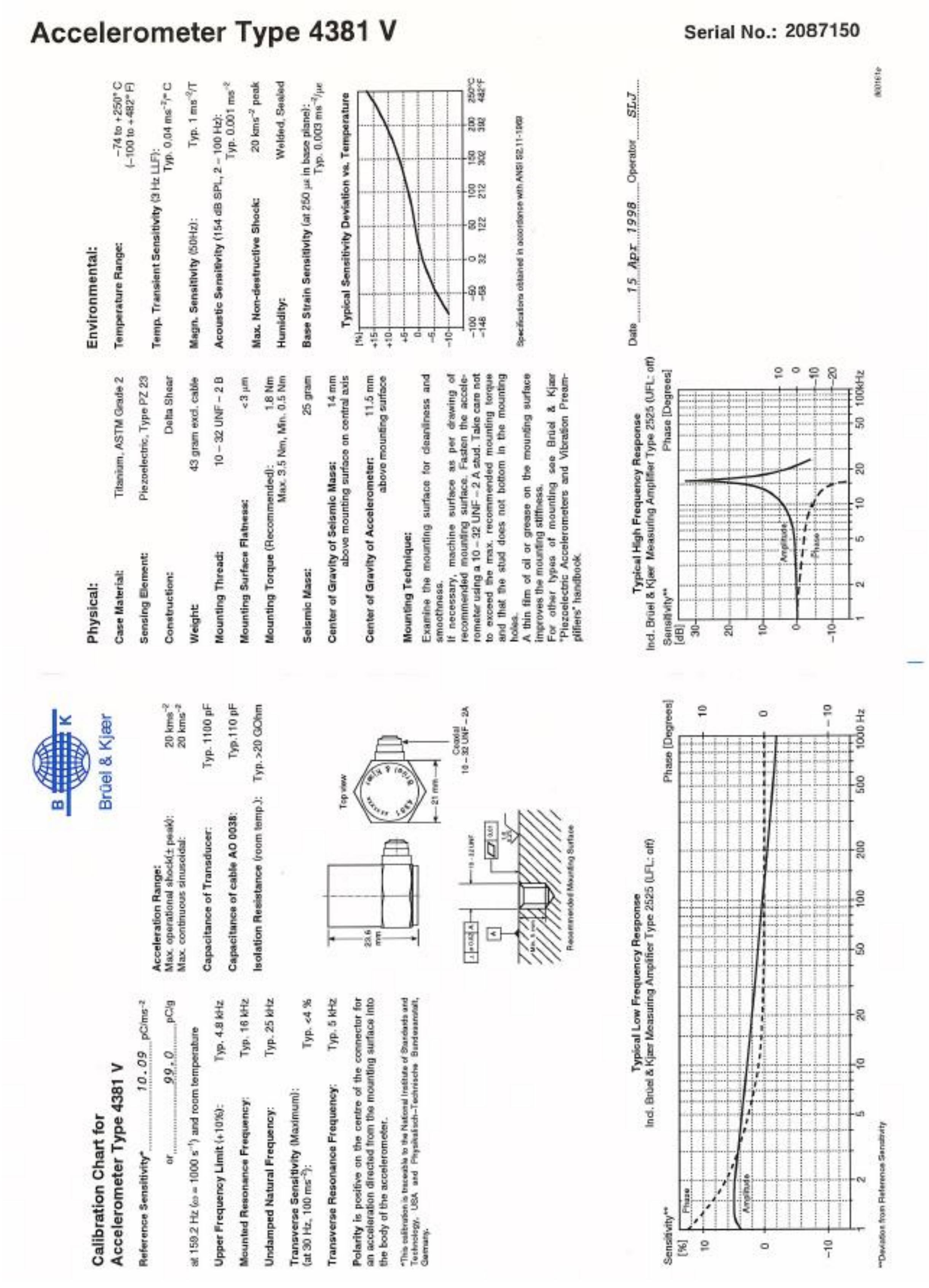


-----END OF REPORT-----

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

8.2. ACCELEROMETER UD

B&K 4381 Pos 1



Accelerometer Type 4381 V

Serial No.: 2087150

Calibration Chart for Accelerometer Type 4381 V

Brüel & Kjær

Reference Sensitivity* 10.09 pC/ms⁻²

or 99.0 pC/g

at 159.2 Hz (ω = 1000 s⁻¹) and room temperature

Upper Frequency Limit (+10%): Typ. 4.8 kHz

Mounted Resonance Frequency: Typ. 16 kHz

Undamped Natural Frequency: Typ. 25 kHz

Transverse Sensitivity (Maximum): (at 30 Hz, 100 ms⁻²): Typ. <4 %

Transverse Resonance Frequency: Typ. 5 kHz

Polarity is positive on the centre of the connector for an acceleration directed from the mounting surface into the body of the accelerometer.

*This calibration is traceable to the National Institute of Standards and Technology, USA and Physikalisch-Technische Bundesanstalt, Germany.

Acceleration Range:
Max. operational shock(± peak): 20 kms⁻²
Max. continuous sinusoidal: 20 kms⁻²

Capacitance of Transducer: Typ. 1100 pF

Capacitance of cable AO 0038: Typ.110 pF

Isolation Resistance (room temp.): Typ. >20 GOhm

Physical:

Case Material: Titanium, ASTM Grade 2

Sensing Element: Piezoelectric, Type PZ 23

Construction: Delta Shear

Weight: 43 gram excl. cable

Mounting Thread: 10 – 32 UNF – 2 B

Mounting Surface Flatness: <3 μm

Mounting Torque (Recommended): 1.8 Nm
Max. 3.5 Nm, Min. 0.5 Nm

Seismic Mass: 25 gram

Center of Gravity of Seismic Mass: 14 mm above mounting surface on central axis

Center of Gravity of Accelerometer: 11.5 mm above mounting surface

Mounting Technique:

Examine the mounting surface for cleanliness and smoothness.
If necessary, machine surface as per drawing of recommended mounting surface. Fasten the accelerometer using a 10 – 32 UNF – 2 A stud. Take care not to exceed the max. recommended mounting torque and that the stud does not bottom in the mounting holes.
A thin film of oil or grease on the mounting surface improves the mounting stiffness.
For other types of mounting see Brüel & Kjær "Piezoelectric Accelerometers and Vibration Preamplifiers" handbook.

Environmental:

Temperature Range: –74 to +250° C (–100 to +482° F)

Temp. Transient Sensitivity (3 Hz LLF): Typ. 0.04 ms⁻²/° C

Magn. Sensitivity (50Hz): Typ. 1 ms⁻²/T

Acoustic Sensitivity (154 dB SPL, 2 – 100 Hz): Typ. 0.001 ms⁻²

Max. Non-destructive Shock: 20 kms⁻² peak

Humidity: Welded, Sealed

Base Strain Sensitivity (at 250 με in base plane): Typ. 0.003 ms⁻²/με

Typical Sensitivity Deviation vs. Temperature

Specifications obtained in accordance with ANSI S2.11-1969

Date 15 Apr 1998 Operator SLJ

Typical Low Frequency Response
Incl. Brüel & Kjær Measuring Amplifier Type 2525 (LFL: off)

Typical High Frequency Response
Incl. Brüel & Kjær Measuring Amplifier Type 2525 (UFL: off)

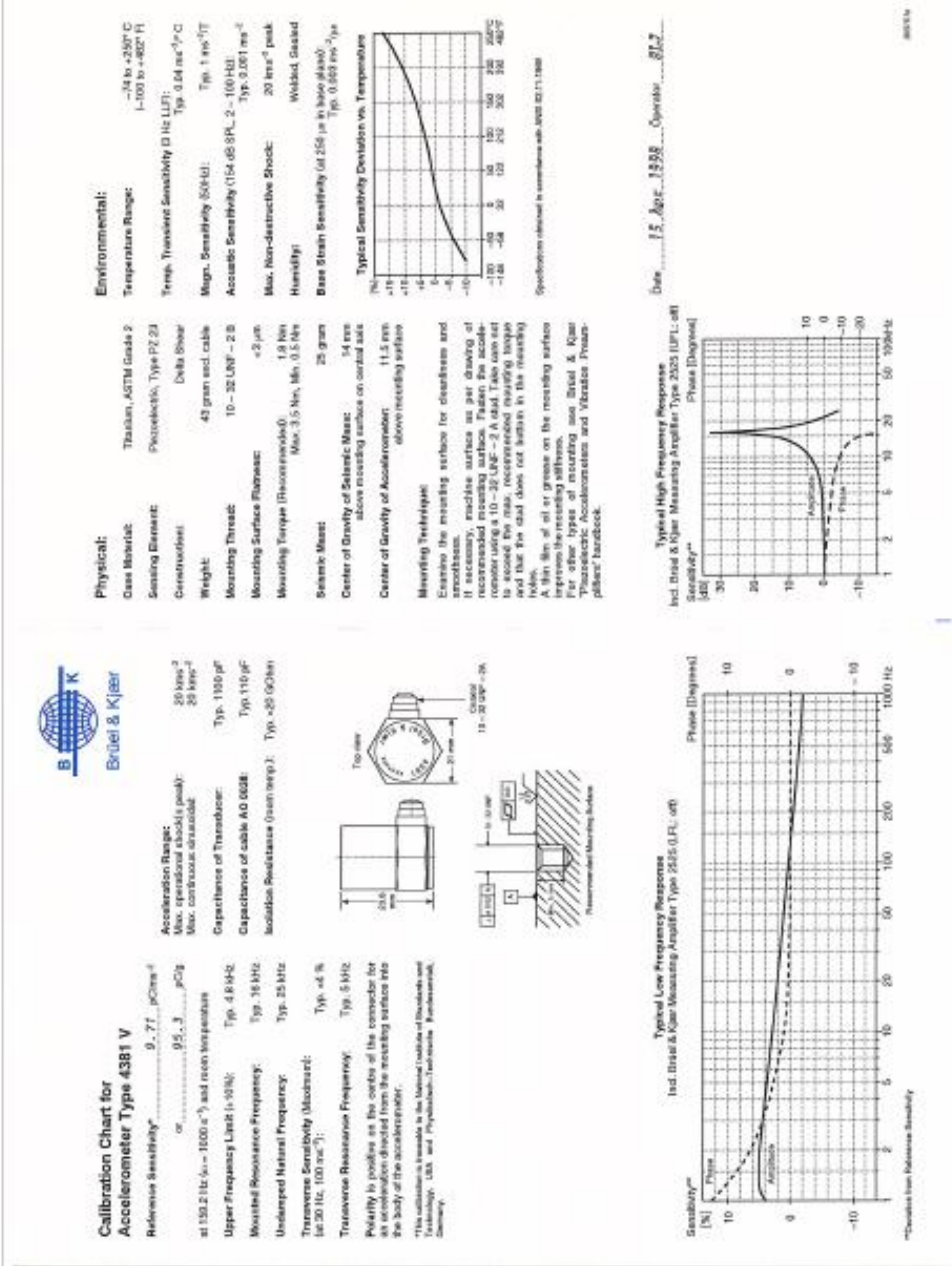
**Deviation from Reference Sensitivity

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

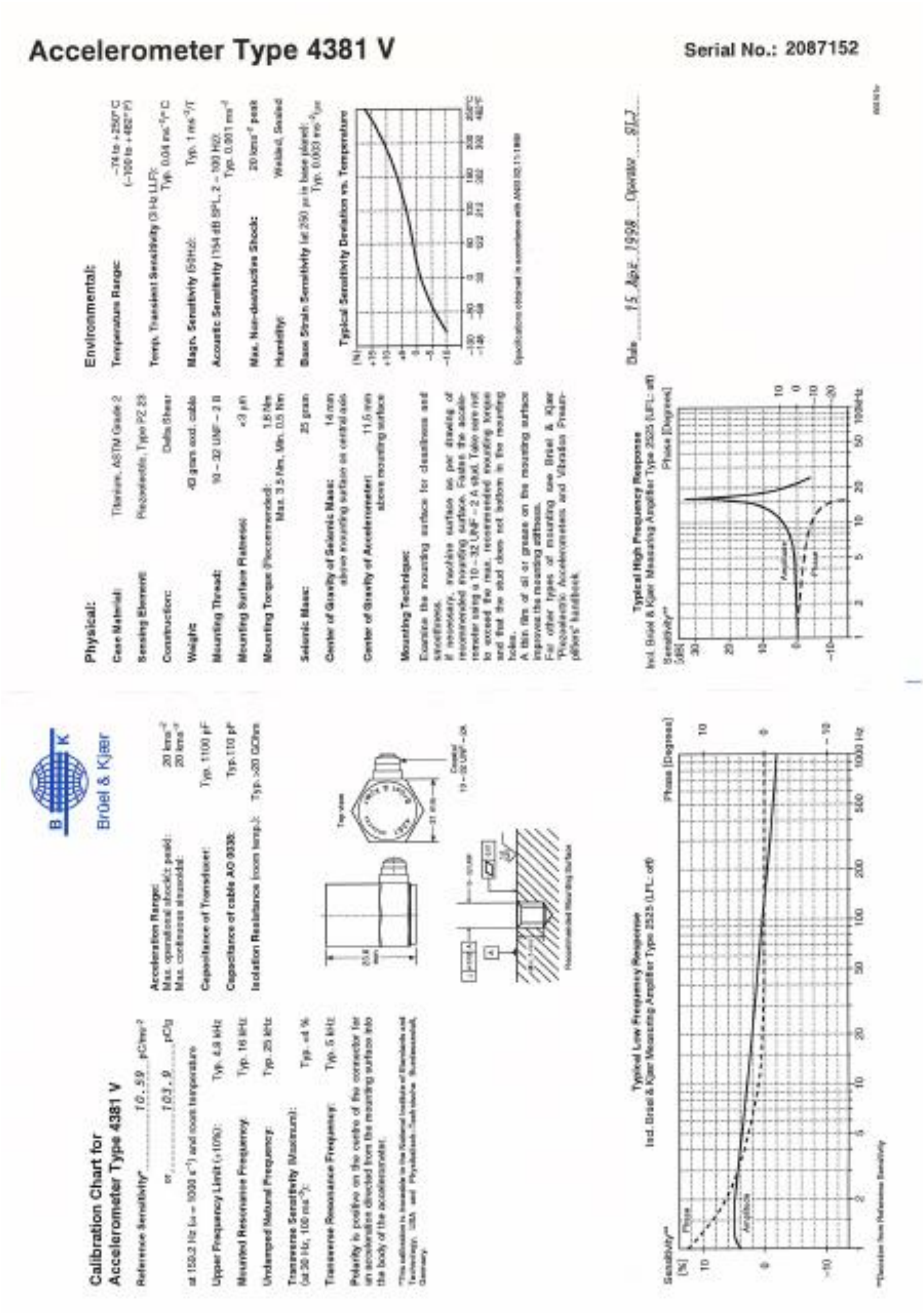
B&K 4381 Pos 2

Accelerometer Type 4381 V

Serial No.: 2087151



B&K 4381 Pos 3


Accelerometer Type 4381 V
Serial No.: 2087152
Calibration Chart for Accelerometer Type 4381 V
Brüel & Kjær
Physical:
Environmental:
Typical Sensitivity Deviation vs. Temperature
Typical High Frequency Response
Typical Low Frequency Response

B&K 4381 Pos 4

Calibration Chart for Charge Accelerometer Type 4381 V

Brüel & Kjær

Serial No.: 10056

Reference Sensitivity [1] at 159.2 Hz (ω = 1000 s^{-1}), 20 ms^{-2} RMS and 22 °C: 9.70 pC/ms^{-2} (95.2 pC/g)

Lower Frequency Limit: Determined by the amplifier used

Upper Frequency Limit (+10%): 4.8 kHz

Mounted Resonance Frequency: 16 kHz

Transverse Sensitivity: Maximum (at 30 Hz, 100 ms^{-2}): < 4% re Reference Sensitivity

Transverse Resonance Frequency: 5 kHz

Calculated values for TEDS [3]: Resonance frequency: 16.9 kHz; Quality factor @ f_{res}: 285; Amplitude slope: -2.3%/decade

Measuring Range: Max. operational shock: ± 20 kms^{-2} peak (± 2000 g peak); Max. continuous sinusoidal: 20 kms^{-2} peak (2000 g peak)

Polarity of the electrical signal is positive for an acceleration in the direction of the arrow on the drawing.

[1] This calibration is obtained on a modified Brüel & Kjær Calibration System Type 9610 System No.: 150117.3 and is traceable to the National Institute of Standards and Technology, USA and Physikalisch-Technische Bundesanstalt, Germany.
The expanded uncertainty is 1.0% determined in accordance with EAL-R2. A coverage factor k=2 is used. This corresponds to a coverage probability of 95% for a normal distribution.

[3] Transducer Electronic Data Sheet according to IEEE P1451.4. Built-in ID-information not included.

[4] Deviation from Reference Sensitivity.

For further information, please see http://www.bk.dk and Product Data Sheet BP 0196.

CE

Electrical:

Capacitance of transducer (excl. cable): 1100 pF

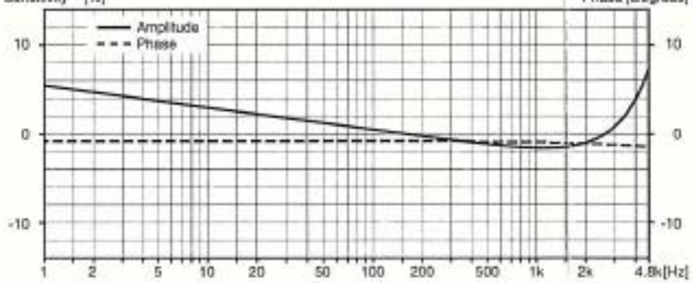
Insulation Resistance sensing element: > 20 Gohm

Ground Loops can introduce error signals. These can be avoided by insulating the accelerometer from the mounting surface using Insulating Stud UA 1215.

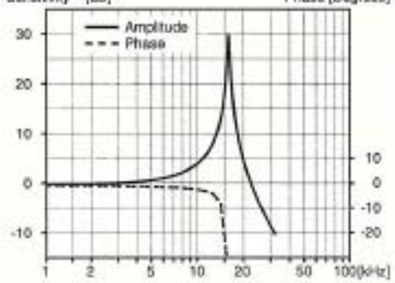
Recommended cable (included): AO 0038

Mounting Technique:
Examine the mounting surface for cleanliness and smoothness.
If necessary, machine surface to a flatness < 10 µm and a roughness < 2 µm.
Fasten the accelerometer using the appropriate stud. Take care not to exceed the recommended mounting torque and that the stud does not bottom in the mounting hole.
A thin film of oil or grease between the accelerometer and the mounting surface helps achieve good contact and improves mounting stiffness.
See also ISO 5348. For other types of mounting, see the Brüel & Kjær handbook "Piezoelectric Accelerometers and Vibration Preamplifiers" (available from your local Brüel & Kjær representative).

Typical Frequency Response



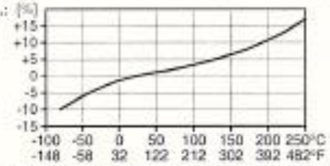
Typical High Frequency Response



Environmental:

Temperature Range: - 74 to + 250°C (- 100 to + 482°F)

Sensitivity Deviation vs. Temp.:



Temp. Transient Sensitivity (3 Hz Low. Lim. Frq. (-3 dB, 6 dB/oct)): 0.04 ms^{-2}/°C

Magnetic Sensitivity (50 Hz, 0.038 T): 1 ms^{-2}/T

Acoustic Sensitivity (154 dB SPL): 0.001 ms^{-2}

Base Strain Sensitivity (at 250 µε in base plane): 0.003 ms^{-2}/µε

Max. Non-destructive Shock: 20 kms^{-2} peak (2000 g peak)

Humidity: 90 % RH non-condensing

Mechanical:

Case Material: Titanium, ASTM Grade 2

Sensing Element: Piezoelectric, Type PZ 23

Construction: Delta Shear®

Sealing: Welded

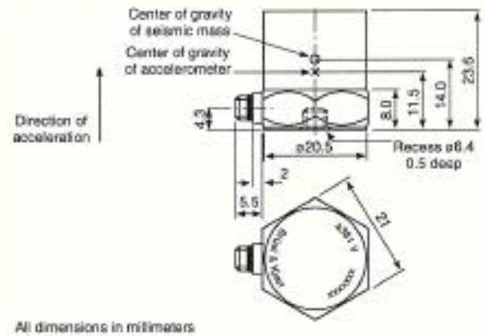
Weight: 43 gram (1.52 oz)

Electrical Connector: 10 - 32 UNF-2A

Mounting Thread: 10 - 32 UNF-2B, Depth 3.2 mm

Mounting Surface Flatness: < 3 µm

Mounting Torque: Max. 3.5 Nm (31 lbf·in). Min. 0.5 Nm (4.4 lbf·in)



Serial No.: 10056

All dimensions in millimeters

Date 19 Jun 2004 Operator CJ

Specifications obtained in accordance with ANSI S2 11-1969 and parts of ISO 5347.
All values are typical at 25°C (77°F) unless measurement uncertainty is specified.

BC 0313-12

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

8.3. SIGNAL ACONDITIONATOR

HBK HOTTINGER BRÜEL & KJÆR
The Calibration Laboratory
Teknikerbyen 28, DK-2830 Virum, Denmark

ilac-MRA DANAK CAL Reg.nr. 307

CERTIFICATE OF CALIBRATION No.: CDK2207124 Page 1 of 11

CALIBRATION OF:

Conditioning Amplifier:	2692	No:	2407075
Identification:	-		

CUSTOMER:

Técnicas y Servicios de Ingeniería, S.L. - TSI
Avenida de Pío XII, 44 - Bajo Izquierda - Edificio
Pyomar - Torre II
28016 Madrid Madrid
Spain

CALIBRATION CONDITIONS:

Preconditioning:	4 hours at 23° C ± 3° C		
Environment conditions:	Air Temperature:	23° C	± 3° C
	Air Pressure:	101.3 kPa	± 5 kPa
	Relative Humidity:	50 % RH	± 25 % RH

PROCEDURE:

The instrument has been calibrated in accordance with the requirements as specified by vendor, using Calibration Procedure No. P_2692_A13.

RESULTS:

[X] As received [ ] Calibration after repair/adjustment

The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor $k = 2$, which for a normal distribution corresponds to a coverage probability of approximately 95 %. The standard uncertainty of measurement has been determined in accordance with EA-4/02
The accreditation assures the traceability to the international units system SI.
Measurements marked with an asterisk (*) are outside our range of accreditation.

Date of Calibration: 2022-09-26 Certificate issued: 2022-09-27

M. Önder
Mikail Önder
Calibration Technician

Erik Bruus
Approved signatory

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

8.4. INCLINOMETER

INCLINOMETER 1 AND INCLINOMETER 2

Protocolo de Verificación	TÉCNICAS Y SERVICIOS DE INGENIERIA, S.L.		TSI
Nº EN INVENTARIO EM-24-01	DENOMINACIÓN INCLINÓMETRO LEVEL DEVELOPMENTS DAS-90-A		
FECHA DE ADQUISICIÓN 19/09/2018	Nº DE SERIE 72171	FECHA DE BAJA	NIVEL DE CONTROL 2
Nº DE ORDEN DE VERIFICACIÓN: **2**		INTERVALO DE VERIFICACION: **BIENAL**	

EJE X			
INCLINACIÓN (º)	INTERVALO ACEPTABLE (º/º)	LECTURA (º)	VALORACIÓN (Ok / No Ok)
-60	-45,7 / -50,5	-48,5	OK
-45	-37,6 / -41,8	-39,6	OK
-30	-26,8 / -29,6	-27,9	OK
30	26,8 / 29,6	28,4	OK
45	37,6 / 41,8	40,4	OK
60	45,7 / 50,5	49,6	OK

EJE Y			
INCLINACIÓN (º)	INTERVALO ACEPTABLE (º/º)	LECTURA (º)	VALORACIÓN (Ok / No Ok)
-60	-45,7 / -50,5	-48,6	OK
-45	-37,6 / -41,8	-39,4	OK
-30	-26,8 / -29,6	-27,9	OK
30	26,8 / 29,6	28,4	OK
45	37,6 / 41,8	40,4	OK
60	45,7 / 50,5	49,4	OK

EQUIPO DE LECTURA UTILIZADO: EM-01-12

OBSERVACIONES:

REALIZADO	REVISADO	APROBADO
FECHA 11/10/22	FECHA 11/10/22	FECHA 11/10/22

9. REFERENCES

1-NI572 R02 - Classification and certification of Floating Offshore Wind Turbines. Bureau Veritas rules and guidelines (2019).

2-NI603 R01 - Current and tidal turbines. Bureau Veritas rules and guidelines (2015).

3-DNV-ST-0126 - Support structures for wind turbines. Det Norske Veritas rules and guidelines (2021).

4-DNV-ST-0164 - Tidal turbines. Det Norske Veritas rules and guidelines (2015).

5-ISO 7919-3 - Mechanical vibration - Evaluation of machine vibration by measurements on rotating shafts — Part 3: Coupled industrial machines (2009).

6- ISO 10816 - Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts — Part 8: Reciprocating compressor systems (2014).

7-VDI 3834 - Measurement and evaluation of the mechanical vibration of wind turbines and their components - Wind turbines with gearbox (2015).

8-D4.3 - Deliverable 4.3: W2Power tower's demonstrator design for its construction in FRP. FIBREGY project, pg 33 (2022).

9-Tdyn RamSeries – Finite Analysis software for structure analyses, COMPASSIS, https://www.compassis.com/en/software/structural-analysis-tdyn-ramseries/.

10- S. Chandrasekaran, T. Chithambaram, S.A. Khader; Structural Health Monitoring of Offshore Structures using Wireless Sensor Networking under Operational and Environmental Variability, International Journal of Environmental and Ecological Engineering, 10; 2016.

11- International Electrotechnical Commission (IEC), IP ratings, https://www.iec.ch/ip-ratings.

12- Digital photography kindly provided Tecnicas y Servicios de Ingenieria (TSI).

13- P. Qiao, K. Lu, W. Lestari, J. Wang; Curvature mode shape-based damage detection in composite laminate plates. Composites Structures. 80, 409-428 (2007).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.