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Identification and Long-Term Tracking of Modal Parameters of a 150m Wind Measurement Mast Using Ambient Excitation

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ABSTRACT
Wind measurement masts are indispensable structures for acquiring data for the wind energy industry and play a central role in assessing the profitability and efficiency of wind projects. As wind turbines have been built taller in recent decades, wind measurement masts must also grow accordingly in order to analyze the wind conditions at these heights. Wind measurement masts are particularly susceptible to vibrations due to their height, slender structure, and exposed position. These vibrations can affect the stability of the mast and reduce the accuracy of the meteorological instruments. For this reason, a 150 m guyed lattice mast at the WiValdi research wind farm was instrumented with 84 uniaxial accelerometers to investigate the structural dynamic behavior of the mast. All measurement components for recording the data were attached to the mast along its entire height of 150 m to minimize the cable paths. The sensors were placed not only on the entire lattice structure itself, but also on the individual booms where the anemometers are located. By simultaneously measuring the weather data, varying environmental parameters can be directly correlated with the modal parameters. This paper aims to provide insights into the preparatory work, installation of the whole measurement chain, and analysis of the measurement data. The results are presented in the form of eigenfrequencies, damping ratios, and mode shapes as functions of varying wind speeds and ambient temperatures over a period of approx. 2 years.

Keywords: Operational modal analysis, influence of environmental parameters, structural dynamics, modal parameters, guyed mast, lattice structure, met mast

1. INTRODUCTION

Guyed masts are tall, slender steel structures that are vertically oriented. Their stability against horizontal forces, such as wind loads, is ensured by guy cables, which are typically attached at multiple levels along the height of the mast. This type of mast construction was developed in the 1930s. After World War II, television and radio began to spread across Europe. As a result, most of the transmission towers for these communication networks were built in Western Europe during the 1950s. With the ongoing expansion of mobile phone networks, the continuous development of such infrastructure remains essential. Therefore, these structures are still relevant today and must be optimized according to the latest technological standards [1]. For this reason, numerous structural dynamic investigations have been carried out on guyed masts in the past to better understand their dynamic behavior and to improve simulation models.

The first experimental studies on guyed lattice masts were conducted by [2] in the late 1980s, where wind speeds and directions were correlated with structural stresses, particularly in welds. It describes a method for predicting the remaining fatigue life based on historical meteorological data, where regular inspections are challenging.

In [3], full-scale measurements were carried out on a 100 m steel tower at the beginning of the 1990s. Three accelerometers were installed on the mast for this purpose. The authors developed a theoretical-experimental approach for the dynamic and aerodynamic identification of guyed structures. The method aimed to validate analytical forecasting models, identified their parameters, and extended their application beyond the typically limited scope of directly measured values.

Windprofiles and statistical parameters of the turbulence structure were determined by measuring the wind speeds on 17 levels of a 341 m guyed masts in [4]. The dynamic response of the mast was evaluated by measuring the strains of the corner legs and the rope forces as well as the accelerations of the mast shaft. Based on the experimental results a system identification was performed. Numerical results were compared with measured ones.

The study in [5] presented results of a measurement campaign of a 67 m microwave communications steel frame tower using accelerometers. Eigenfrequencies, damping ratios, and mode shapes were determined by measuring the dynamic responses of the tower and found to be in good agreement with the finite element model.

A novel approach of stochastic subspace identification was presented in [6] which was validated with real vibration data from a 30 m steel transmitter mast excited by wind load. The measurement setup for the dynamic test consisted of 23 sensor positions. The system identification was carried out in a frequency range of 0 to 5 Hz. A total of seven mode shapes were identified.

Computational structural analyses of guyed steel telecommunication towers for radio antennas were investigated in [7]. Static and dynamic analysis results were presented for three different guyed towers (50, 70, and 90 m high).

A method for identifying modal wind loads using full-scale structural response data from a 9.1 m guyed mast was presented in [8]. The approach relies solely on measurement data, without needing additional information about the structure's properties or the wind conditions. Modal parameters were obtained using Operational Modal Analysis (OMA) from ambient vibration data. The procedure's validity was confirmed by comparing field results with numerical simulations, showing it can be applied to other structures with similar complexity.

2. OVERVIEW OF THE MEASURING CHAIN

2.1. Framework

The Research Wind Farm *WiValdi* (Wind Validation) in Krummendeich, Germany, is a unique research facility operated by the German Aerospace Center (DLR) and enables scientific studies at full-scale under real environmental conditions. WiValdi consists of two Enercon E-115 EP3 E4 wind turbines (each 4.2 MW), an additional experimental wind turbine, and four meteorological measurement masts. The first mast is located in front of the first wind turbine, followed by a mast array with three additional masts behind the first turbine. Behind the mast array, there is the second wind turbine. An overview of the wind farm can be seen in Fig. 1. WiValdi is equipped with advanced measurement systems to monitor wind conditions, turbine behavior, and structural loads, offering valuable data to improve the efficiency and reliability of wind energy systems. The research conducted at WiValdi aims to advance the understanding of wind turbine dynamics, facilitate the development of more robust and energy-efficient turbines, and enhance the integration of renewable energy into the power grid. This initiative supports the transition to a more sustainable energy future and provides crucial insights for both industry and research.

Figure 1: Overview of the WiValdi Research Wind Farm in Krummendeich, Germany. In the foreground is the 150 m mast, followed by the first wind turbine and the mast array. Behind the array is the second wind turbine. At this point (as of January 2025), the experimental turbine is currently under construction.

2.2. Met mast details

The first mast in front of the first wind turbine is a 150 m guyed lattice mast which is equipped with the necessary measurement technology to perform certification measurements according to the IEC 61400 standard. Additionally, it is equipped with extensive supplementary instrumentation to measure the wind field flowing into the first wind turbine from the ground up to the rotor blade tip at a height of 150 m. The mast consists of 50x3 m segments. Each element is designed as a steel tubular truss with a triangular base. On a total of six levels, three-armed booms are installed to mount various sensors to measure wind speed and direction, temperature, humidity, and air pressure. Rain sensors and gas analyzers are also installed on the mast. Furthermore, a large number of accelerometers were installed along its entire height to analyze the mast's vibrational behavior. This setup enables the identification of the mast's modal parameters, as well as the tracking of eigenfrequencies and damping ratios depending on factors such as wind speed and ambient temperature.

2.3. Sensor setup

A total of 84 uniaxial accelerometers (type: MEAS 8811LF-01-005, sensitivity $\pm$ 5g) were installed to measure the response of the structure. The selected sensors are specifically designed for outdoor applications. The sensors were mounted on the individual mast segments and booms at ground level before the mast was assembled, see Fig 2. For this investigation, 30 sensors were installed directly on the mast, while the remaining sensors were mounted on the booms where the meteorological measuring

Figure 2: Instrumentation of the sensors on the ground at the construction site. Left: biaxial measurement point on a mast segment. Right: triaxial measurement point at the end of a boom tube.

instruments are installed. Custom adapters were manufactured for the sensors on the mast, each capable of holding two sensors. For the measurement positions on the booms, adapters were designed to hold three sensors each. As a result, there are 15 biaxial measurement points on the mast and 18 triaxial measurement points on the booms. The sensors on the mast were aligned radially and tangentially to the steel tube. The sensors on the booms were positioned axially, radially, and tangentially to the boom tube. A sensor plan of the accelerometers is shown in Fig. 3.

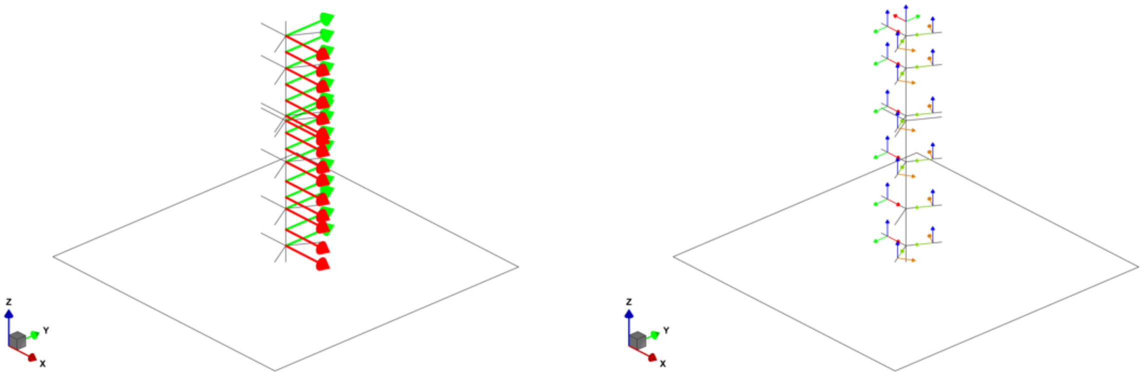

Figure 3: Sensor layout including 84 uniaxial accelerometers: Left: 30 sensors attached to the mast, Right: 54 sensors attached to the booms.

2.4. Measurement system

A measurement system from *imc Test & Measurement GmbH* is used for data acquisition. The measurement amplifiers are eight-channel IEPE/ICP modules. A total of 14 of these modules are installed. The connection of ICP-compatible sensors is made via BNC connectors. A key advantage of this measurement system is its modular design, which allows the modules to be interconnected and spatially distributed. The systems use the EtherCAT standard as the internal system bus to connect the modules. The system was divided into five control cabinets and distributed across the entire height of the mast to keep the cable lengths of the sensors on the 150 m mast as short as possible. The data is sampled at 200 Hz. The acquisition system is set to generate 10 min files, which means that each channel contains 120,000 samples. Each file is approx. 50 MB in size. The data is stored locally on a PC and transferred remotely at regular intervals.

2.5. Control cabinets

Five identical control cabinets were constructed by DLR. Each of these cabinets contains the measurement modules, a power supply, surge protection modules, and fans as main components. The cabinets were positioned at heights of 28, 60, 83, 118, and 138 m to keep cable lengths as short as possible. The control cabinets were preassembled on the ground before the mast was erected. After the mast was completed, cables for power supply, networking, and grounding were installed in collaboration with industrial climbers. An overview of the cabinets during the final commissioning in the laboratory can be seen in Fig. 4. In addition to the five distributed cabinets, there is another large cabinet at the base of the mast, which houses additional measuring systems for the meteorological sensors and data acquisition PCs. In our case, a *Cincoze DX-1100* is used for data acquisition which is a rugged workstation designed for high-performance computing in demanding industrial environments. All other components of this setup are also designed to withstand changing environmental conditions and record measurement data around the clock.

Figure 4: Final check of control cabinets before the installation. The measuring modules are connected to each other with a patch cable.

3. SYSTEM IDENTIFICATION

This section presents the results of the modal identification using OMA with a classical data-driven Stochastic Subspace Identification (SSI-DATA) algorithm from the DLR in-house MATLAB toolbox [9]−[10]. For the evaluation and modal identification of the structure, this paper will only use the 30 installed accelerometers that are directly attached to the mast. The remaining 54 accelerometers, located on the booms, will not be used for further analysis here. A representative 10 min dataset with sufficiently high wind excitation was found on January 6, 2025. During this period, the cup anemometer on the mast at hub height (90 m) measured an average wind speed of approx. 21 m/s. The ambient temperature was about 9 °C. The data were decimated from 200 to 10 Hz before the identification. The acceleration time history of the 30 sensors during this period can be seen in Fig. 5.

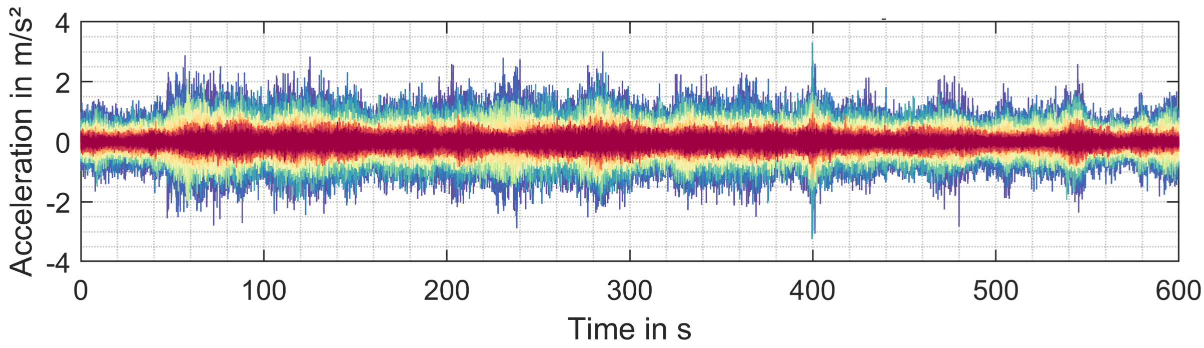

Figure 5: 10min acceleration data on January 6, 2025 / 5:00 to 5:10 pm.

The resulting stabilization diagram is shown in Fig. 6. Lines of consistent poles at increasing model orders can be observed. The model order was set to 100. In a frequency range of 0.8 to 3 Hz a total of 12 modes could be identified. These modes appear in pairs with nearly identical eigenfrequencies which represent the global bending modes of the mast in the x- and y-direction. This structural dynamic behavior, where modes occur in pairs with closely spaced eigenfrequencies, is already known from tower modes of wind turbines, see for example [11], [12] or [13]. So, the 12 modes are 6 pairs of 1st to 6th bending mode of the mast. A visualization of the mode shapes can be seen in Fig. 8 and Fig. 9.

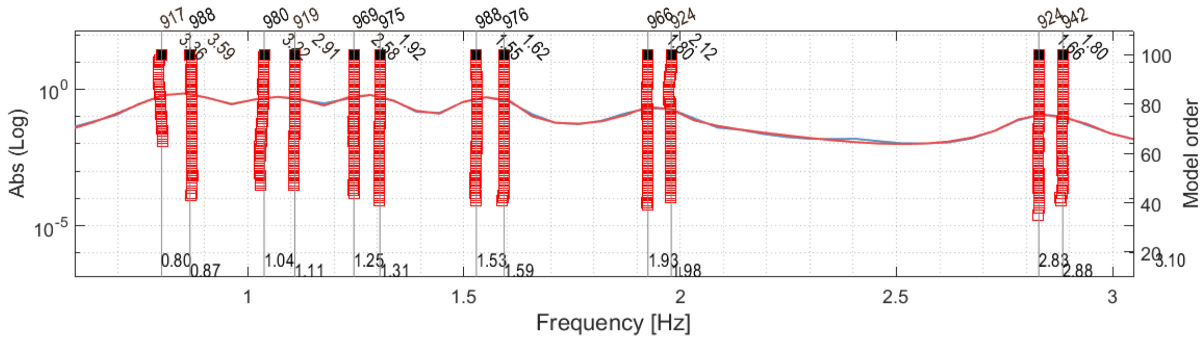

Figure 6: Stabilization diagram from SSI using 30 accelerometers.

4. MODE TRACKING

Based on the initial analysis in Section 3. the modal parameters (eigenfrequency and damping ratio) of these 12 modes were then tracked as a function of wind speed and ambient temperature over a period of approx. 2 years. The data acquisition at the wind measurement mast began on January 26, 2023 and stopped for this paper on January 31, 2025. For the mentioned period, theoretically 106,026 10min datasets would be available. In reality, a total of 83,396 10min datasets were recorded, which corresponds to approx. 79% of the possible measurement data. At the beginning of the measurement in January 2023 the entire setup was not yet stable enough to record data around the clock. In some cases, the power supply at the mast failed and the measurement system could not yet be restarted remotely. This is the reason why some data is missing. It is not an easy task to set up a measurement system that is supposed to record data 24/7 for several years. Many problems can arise that were not considered in advance. It starts with ensuring that the hard drives do not constantly fill up, that the measurement system and computer automatically restart after a power outage, and so on. The entire measurement chain must be remote-capable so that one does not have to constantly travel to the investigated structure to fix errors.

The recorded measurement data cover a wind speed range between 0 and 24 m/s and a temperature range from -7 to $+29$ °C. In Fig. 7, it can be seen that the different clusters were identified with varying success rates. Particularly, the modes for the 4th and 5th bending pair were identified at a lower rate compared to the first three mode pairs. The first two mode pairs were identified with the highest success rate. In the measurement data with varying wind speeds, it can be seen from the color bar that the damping decreases as the wind speed increases (yellow). It can also be observed that the damping ratios vary across all the analyzed 10min datasets. This is a known behavior in OMA where damping is a parameter that comes with a high degree of uncertainty. No clear trend can be observed with varying temperatures. The damping values of the different modes fluctuate randomly, regardless of the temperature.

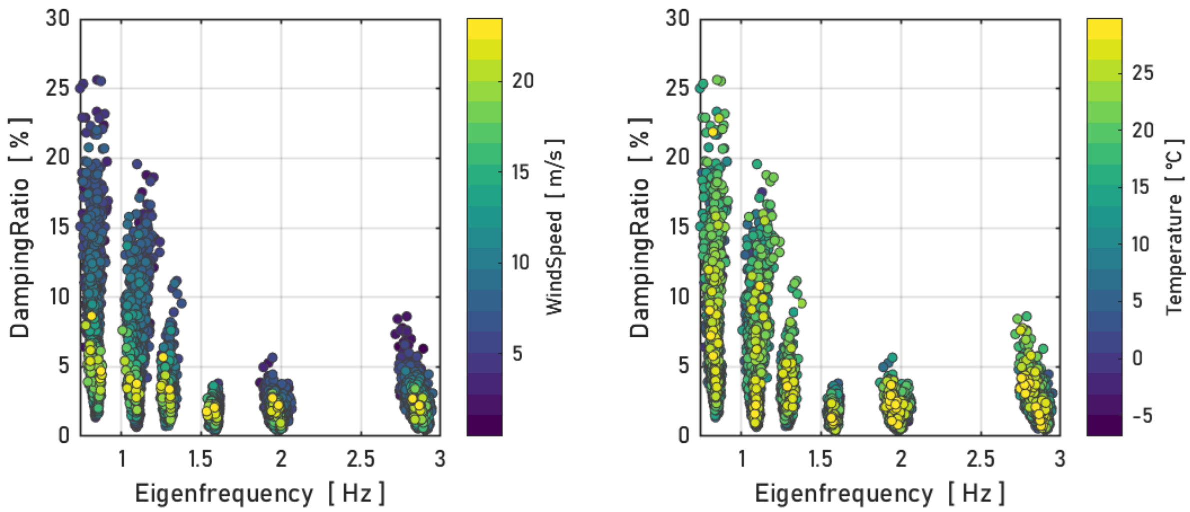

Figure 7: Identification of 83,000 10min datasets. Left: Eigenfrequencies and damping ratios as a function of varying wind speeds. Right: Eigenfrequencies and damping ratios as a function of varying ambient temperatures.

As mentioned in [14] when investigating varying parameters, all other possible parameters that may have an influence should be kept as constant as possible. This was not considered in this evaluation. This means that when analyzing varying wind speeds, the influence of the temperature was ignored. The same applies to the tracking of temperature, where the possible influence of wind speed was ignored. Therefore, when analyzing modal parameters as a function of an ambient parameter, one should use datasets where the other ambient parameters are approximately constant. As an example, one could use only datasets where the average temperature ranged between 5 and 6°C when investigating the influence of varying wind speeds on the modal parameters. However, this reduces the usable datasets or requires a data base spanning several years.

5. CONCLUSIONS

This article presents the instrumentation of a 150 m guyed lattice mast in the WiValdi research wind farm. The mast was equipped with a total of 84 uniaxial accelerometers. Due to the size of the structure and the number of the sensors, the measuring system used had to be distributed over the height of the mast so that minimum sensor cable lengths could be realized. In preparation, a total of five identical control cabinets were built by DLR to house the required measurement system and to protect it from the changing environmental conditions. The sensors and control cabinets were attached to the individual mast segments on the ground at the construction site before the mast was erected. Once the mast had been erected, all the sensor cables were connected to the respective control cabinets and the entire measurement chain was put into operation. The entire measurement concept was designed in such a way that measurement data can be recorded around the clock in 10min time blocks. Continuous measurement data acquisition started in January 2023 and has been running 24/7 since then (with the exception of a few outages). This paper showed how a 10min dataset was analyzed with a classical data-driven OMA SSI method and how 12 global modes of the mast were identified in a frequency range between 0.8 and

3 Hz. In addition to the acceleration data, meteorological measurements such as wind speed and ambient temperature were also available, allowing the modal parameters of approx. 83,000 10min datasets (as of January 2025) to be tracked as a function of these variables. The results have shown that with increasing wind speed, the damping values of the 6 mode pairs decrease. However, the influence of varying ambient temperatures did not show any clear trend.

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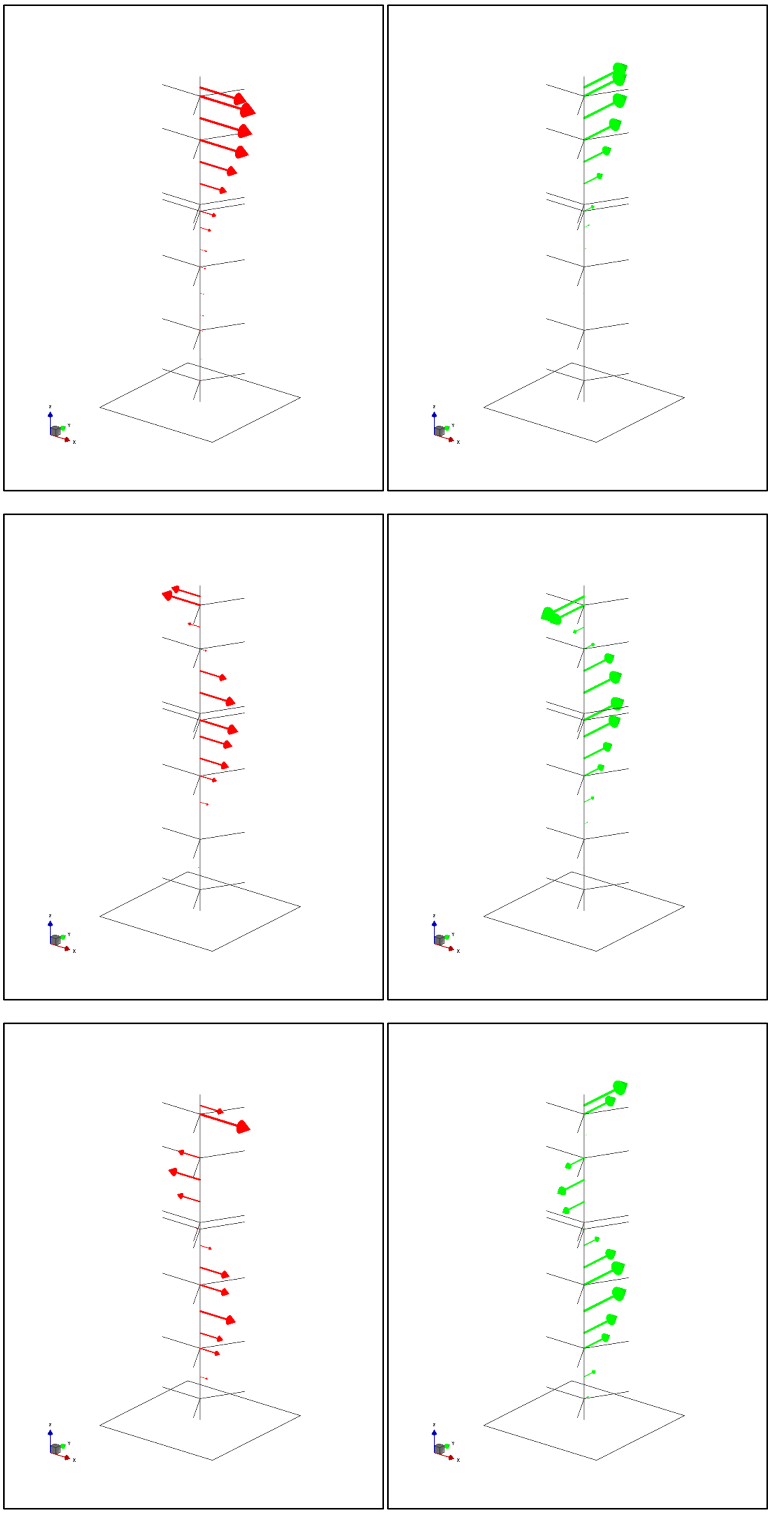

Figure 8: Overview of the identified mode shapes. 1st column: 1st to 3rd bending in x-direction. 2nd column: 1st to 3rd bending in y-direction.

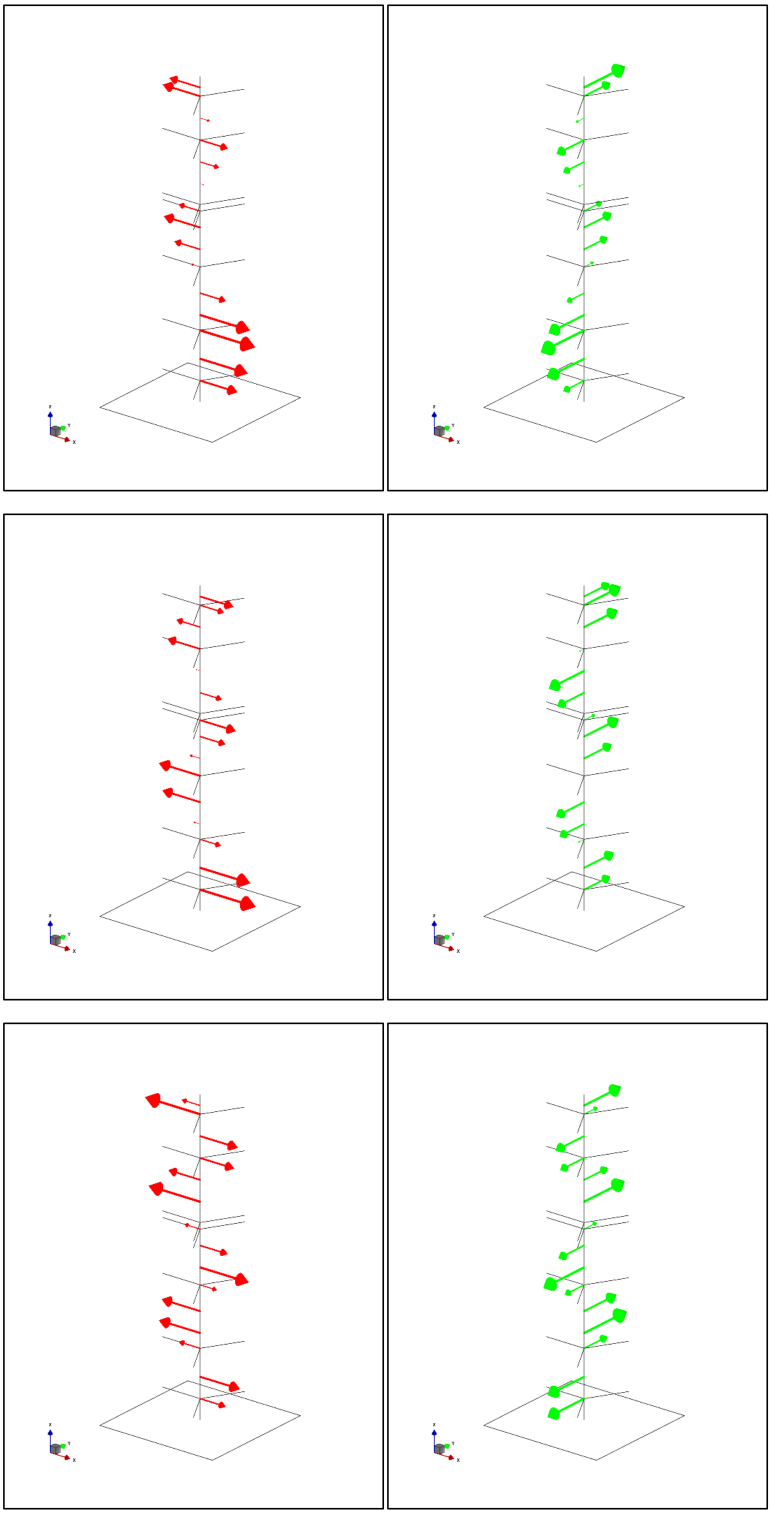

Figure 9: Overview of the identified mode shapes. 1st column: 4th to 6th bending in x-direction. 2nd column: 4th to 6th bending in y-direction.