SMAR 2019 – Fifth Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2019

Vibration Analysis of Structures using a Drone (UAV) based Mobile Sensing Platform

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ABSTRACT: The identification of the dynamic behavior of structures, like bridges and towers, is relevant to address multiple issues. In many cases the dynamic parameters should be acquired only once or at a frequency that doesn't justify the installation of distinct vibration sensors for a long-term monitoring. To identify modal frequencies of a structure, a drone based mobile sensing platform has been implemented. This sensing platform measures the relative displacement between the structure and the drone, which also shows a strong dynamic behavior under wind turbulences. By regarding the dynamic model of the drone and additional measurements at the distance sensor the absolute movement of the structure can be estimated based on the measured relative distance. This time domain data is a suitable input for various operational modal analysis algorithms. The system has been used to identify the dynamic properties of test and real structure, like a 1.5 MW wind turbine tower.

1 INTRODUCTION

There are several reasons to implement observation and inspection strategies at civil structures to gain knowledge about new construction methods, to get information about the location specific conditions, like ground and environmental conditions the impact of live loads and the change of damage relevant indicators over time. A sophisticated instrument for a continuous observation of a civil structure is structural health monitoring where a heterogeneous setup of sensors is applied at or close to a structure for a defined purpose. The time frame for these measurements can vary from a short-term period of days/weeks where construction critical works are realized to a long term period of some years to gain information about cyclic (daily and annual) structure specific impact. A recent example is the study of the long-term behavior of the Rednitztalbrücke in Germany, which is a 170 m long integral railway bridge, see Wenner et al. (2018). To investigate the actual deformation behavior of the structure including the impact at the continuous ballasted track and rails. These measurements are compared to a numerical model of the bridge including the soil ground, that shows an impact on the static and dynamic behavior of the structure. For wind turbines a condition monitoring at the wind turbines power train is typically integrated in the SCADA (Supervisory Control and Data Acquisition) system as well as onshore and offshore wind power plants. Additional implemented structural health monitoring systems, which perform vibration, inclination, strain and acoustic emission measurements are installed at the foundation structure, the tower and the rotor blades. These measurements are used to detect changes of the static and dynamic properties of the structure at an early state using data analytics like subspace-based damage detection algorithms, see Hille (2018). The results of such algorithms are damage indicators, that are correlated to a global damage development. Those systems require sensors that are installed at the structure permanently. The effort is quite high for the measurement equipment (unit price, installation, calibration and maintenance costs) and the necessary infrastructure like power supply and communication for data transmission. The benefit of the monitoring should be preponderance regarding the costs for the structural integrity monitoring, like in Thöns et al. (2015). So, one part of the solution is to reduce the costs for the data acquisition by periodically repeated short term measurements, that are highly automated.

In this paper we first describe the related work (Section 2). In Section 3 we present a quadcopter-based unmanned aerial vehicle (UAV) equipped with additional sensors and measurement systems. We introduce an approach to identify the dynamic properties of a building structure using this mobile sensing platform. The experimental validation is presented in Section 4, where the proposed system measures the vibration frequency of a wind turbine tower. Finally, in Section 5 conclusions and an outlook for further directions of research is given.

2 STATE OF THE ART

2.1 Operational Modal Analysis

The system identification of a vibrating structure is the process to gain a modal model from a real structure by means of measurements. The vibration behavior is described by parameters like eigenfrequency, damping ratio, mode shape and modal participation factors. If the vibration is excited by an artificial source that is measured, the modal shapes can be scaled according to the excitation. This is called ‘experimental modal analysis’. If the excitation is not measured, e.g. because they are difficult to obtain, like in the case of ambient vibration excitation, the process is called ‘output only identification’ or ‘operational modal analysis’ (OMA) and relies on the measured vibration response of the structure. It is assumed that the excitation signal has a stochastic property like the model of white noise.

Usually for an OMA, the sensors will be fixed to the structure. In Bigelow et al. (2017) the dynamic behavior of a composite frame rail-way bridge has been measured under several load conditions, like a hydraulic shaker excitation and ambient excitation using piezo-electric accelerometers. Not only temporarily installed sensors are used, also permanent installed optical fibers perform a distributed strain measurement using optical time domain reflectometry techniques (C-OTDR) to identify eigen frequencies and eigen shapes of a structure, see Liehr et al. (2018). The result of an OMA is used for model updating of a finite element model, e.g. to compare damaged and undamaged structure states or changes in structures’ behavior under changing temperature conditions, like in Ozcelik (2019).

2.2 Autonomous Unmanned Vehicle

An unmanned aerial vehicle (UAV) is an aircraft without a human pilot aboard. The size and payload can vary from a wing span of centimeters and payloads of grams (micro drones) to real size aircrafts. A multicopter is a rotorcraft with more than two rotors. In the special case of a quadcopter, it is a rotorcraft with four vertically oriented propellers, where the two rotor pairs always rotate in opposite directions. The flight maneuvers are controlled by individual variations of the rotor speeds. In the ideal case all rotors have the same speed and the quadcopter is in a hover flight, where it maintains its fixed position. The quadcopter can move in all six directions to approach its destination and rotate around the center axis. To accelerate in horizontal direction, it

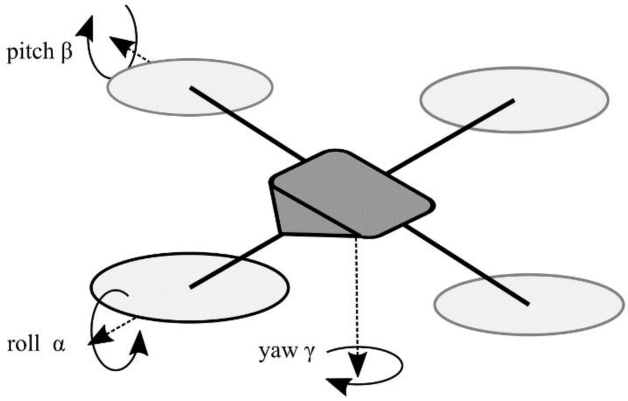

Figure 1. Rotation axis definitions of an unmanned aerial vehicle.

needs to tilt. For the estimation of the motion state for a stable flight position, the UAV is equipped with embedded internal sensors (gyrometers and accelerometers).

The motion model of a UAV can be described by a twelve-dimensional state vector $\mathbf{x} \in \mathbb{R}^{12}$, like in eq. 1

$$\mathbf{x} := \left(x_t, y_t, z_t, \dot{x}_t, \dot{y}_t, \dot{z}_t, \alpha_t, \beta_t, \gamma_t, \dot{\alpha}_t, \dot{\beta}_t, \dot{\gamma}_t\right), \tag{1}$$

where the components x_t, y_t, z_t demotes the position of the quadcopter and the components $\dot{x}_t, \dot{y}_t, \dot{z}_t$ the velocity, both related to the fixed environment. The state vector contains the roll angle α_t, the pitch angle β_t and the yaw angle γ_t of the drone, as well as the rotational speed along the corresponding axis, see Fig. 1.

Quadcopters are widely used as a platform to carry photo and video cameras. In the field of civil engineering its applications cover e.g. documentation of building processes, building assessment, thermal leakage identification and photogrammetric applications like the generation of a 3D Model of a structure. Drones can be used to carry any kind of sensing equipment, like gas sensors to explore released gases in the environment. The drone can also be used to measure wind speed and direction, like in Neumann and Bartholmai (2015).

3 HYPOTHESIS AND METHODS

To identify the vibration parameters of a structure by operational modal analysis, the response of the structure needs to be measured. Typically, the vibration acceleration, the vibration velocity or the vibration deflection are measured by the corresponding sensors, that are sensitive enough and fit in their dynamic behavior to the frequency range of the structure under test. Usually the sensors need to be attached to the structure, e.g. for accelerometers and geophones (velocity) or pointed towards the structure from a stable and fixed reference point, like Laser Doppler vibrometers (velocity) and geodetic laser tracker (distance). The setups always require a high effort to install and place the sensors to achieve the excellent mechanical connection between the structures surface and the sensor or to find a fixed reference position for the vibrometer on the ground. Often, like in the case of wind turbines, the vibration movement direction and the measurement direction are not aligned. In this paper a mobile sensing platform is proposed. An unmanned aerial vehicle (UAV) can be used to position an optical sensor at the relevant position of the structure, see Fig. 2. In contrast to a static measurement from a fixed reference point the UAV shows a strong vibration behavior itself. The change from a fixed to a mobile measurement base plane poses a major challenge for the signal analysis, as the dynamic behavior of the mobile sensing platform (see Section 2.2) will affect the measured vibrational behavior of the structure in multiple ways.

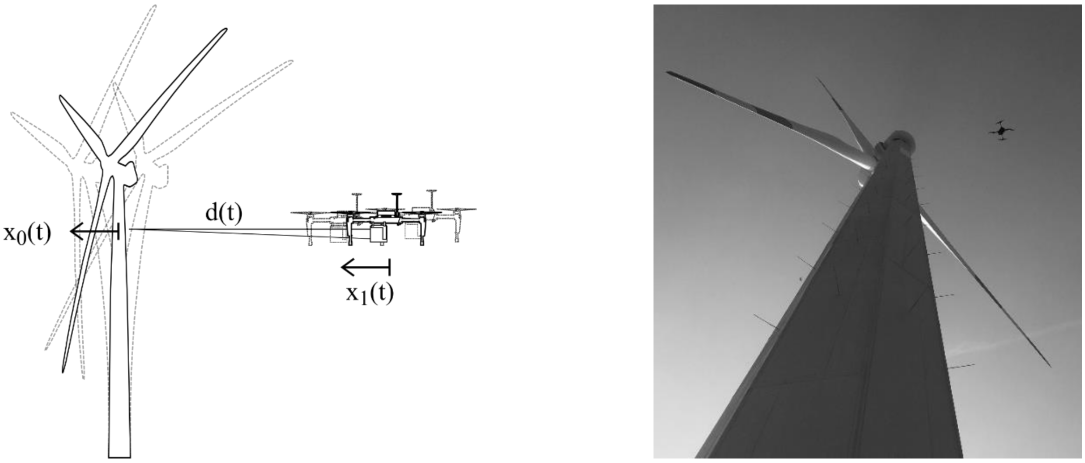

Figure 2. An unmanned aerial vehicle (UAV) carries an optical displacement sensor to perform a vibration measurement. Left: Function principle. Right: Actual measurement at Timber Tower (see Section 4).

During the measurement the UAV is controlled to hover at a certain position and orientation with respect to a global frame, called the target pose. Environmental influences like wind as well as noise in the onboard sensor measurements of the drone lead to deviations from the target pose. The displacement and rotation of the UAV, originating from deviation of target pose as well as control operations to re-establish the target pose, can be of several orders of magnitude larger than the vibrational motion of the structure. Regarding the UAV movement as noise in the measurement leads to very low signal-to-noise ratios below 1:1 (< 0 dB). If the sought modes of the structure lie in the same frequency range like the UAV movement, which they commonly do in the case of large structures, it is not possible to directly estimate eigen modes from the measured distance signal without a high (~10:1) signal-to-noise ratio.

In the following a method for compensating the UAV movement in the measured distance signal and identifying modal parameters despite low signal-to-noise ratio is proposed, using only a minimum number of three additional sensors (see Fig. 3). It is assumed that the UAV is capable of maintaining the target position, with deviations from the pose not exceeding the distance measuring range. Additionally, it is required that the UAV will realign itself with the measurement axis in case of deviations in orientation, such that the yaw angle is approximately zero on average. The method aims at compensating the UAV displacement in the measured distance signal, therefore the displacement of the UAV has to be obtained by double integration of acceleration measurements.

The first step is to reconstruct the displacement x_1 of the UAV projected onto the measurement axis, with the roll angle a_t, the pitch angle β_t and the yaw angle γ_t:

$$x_1 = x_t(t) \cdot \cos\beta_t(t) \cdot \cos\gamma_t(t) \ + y_t \cdot \sin\gamma_t(t) \cdot \cos\alpha_t(t) + z_t \cdot \sin\beta_t(t) \cdot \cos\alpha_t(t). \quad (2)$$

By far the larger contribution to the displacement x_1 stems from the UAV moving in its local x-axis rather than the y- or z-axis. Given a sufficiently stable orientation and altitude control of the UAV, which can either be achieved by the common onboard sensors like GPS and multiple IMUs or additional optical stabilization, β_t and z_t are small and thus the y- and z-axis movement can be neglected.

The x-axis displacement x_t can be obtained from double integration of the acceleration in x-direction, which can be measured using an accelerometer.

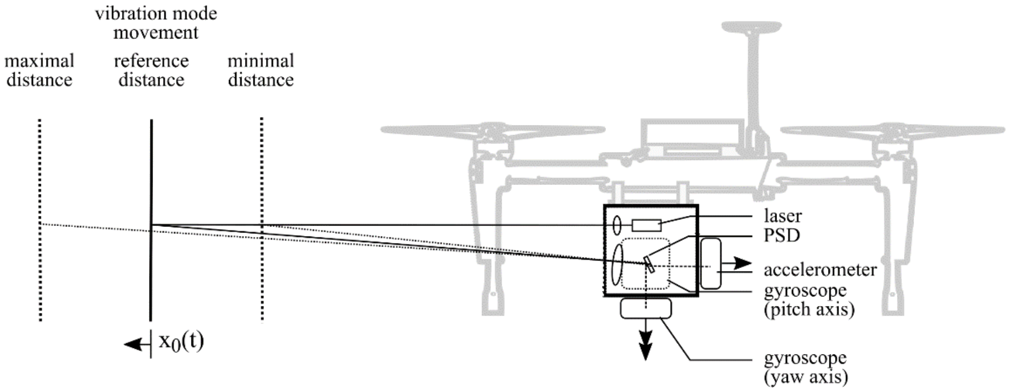

Figure 3. Measurement head containing triangulation displacement sensor and two accelerometers.

Pitch and roll motion of the UAV will rotate the x-axis accelerometer, causing it to partially measure gravity as well. Compared to the small accelerations during hovering, the gravitational influence is rather large, even for small angles. This makes it necessary to subtract the gravity out of the acceleration, which requires the pitch angle β_t as well as the roll angle α_t:

$$x_t(t) = \int\int \ddot{x}_t(t) - g \cdot \sin\beta_t(t) \cdot \cos\alpha_t(t)\, dt\, dt. \tag{3}$$

The roll angle α_t will only affect the measurement when the pitch angle β_t is significant at the same time, which will rarely be the case during hovering and thus can be neglected:

$$x_t(t) \cong \int\int \ddot{x}_t(t) - g \cdot \sin\beta_t(t)\, dt\, dt. \tag{4}$$

The required pitch and yaw angles could be obtained directly by estimating orientation from three accelerometers. Since the UAV will accelerate even during hovering to hold its position, the angle estimation is flawed. Using a MEMS gyroscope that is nearly unaffected by acceleration will yield precise estimations of the angle by integration of the angular velocity. The distance d_t is measured with respect to the local frame of the UAV and has to be projected to the measurement axis. This depends also on the surface of the structure, for a flat surface it is given by:

$$d(t) = d_t(t) \cdot \cos\beta_t(t) \cdot \cos\gamma_t(t). \tag{5}$$

Thus, the structural response $x_0(t)$ in the time domain can be approximately determined as:

$$x_0(t) = d(t) + x_1(t). \tag{6}$$

To accurately identify modes of structures whose main eigenfrequencies are usually very low (~0-30 Hz), it is necessary to take measurements of several minutes duration to achieve the necessary frequency resolution, which is the reciprocal of the total measurement time or window size. From a technical point of view, it is difficult to obtain accurate estimates for the displacement x_1 as well as the yaw and pitch angles over a long measurement period (>10s). The reason is that small errors add up in the integration and lead to drift in the integrated signal. A common approach to counter this is to introduce additional sensors that can measure the parameters directly but at a lower rate, e.g. GPS, and then fuse the readings with the estimations using a Kalman Filter to correct the absolute value. This is necessary in the case of navigation, where the absolute position and orientation is of interest. In this scenario however, the absolute position of both the structure and the UAV is constant on average. Instead, the change in position occurring in a specific frequency range is sought, which can be obtained without additional sensors by filtering the signals to remove low frequency drift and high frequency noise. With eq. (6) it is clear that preserving the phase of all signals during filtering is of upmost importance to achieve precise measurements, because a phase distortion of one signal shifts the signal in the time domain and thus distance and displacement become uncorrelated in time. Since the measurement can be analyzed offline, causality is not a requirement and thus infinite response (IIR) filters can be used as zero-phase filters by applying a recursive filter forward and backward in time. This is advantageous over using a finite response (FIR) filter, as the FIR filter is computationally more expensive and will introduce a constant phase shift which has to be subtracted from the measurement time. The resulting filtered structural response $x_0(t)$ can be analyzed in the time domain, e.g. with Stochastic Subspace Identification, or in the frequency domain by simply applying Fourier transform (FFT) or more advanced modal analysis techniques like the aliasing free polynomial method.

4 EXPERIMENT AND RESULTS

In order to test the hypothesis, a prototype of a mobile sensing platform has been developed as can be seen in Fig. 4. The prototype is based on a DJI Matrice 100 quadcopter development platform.

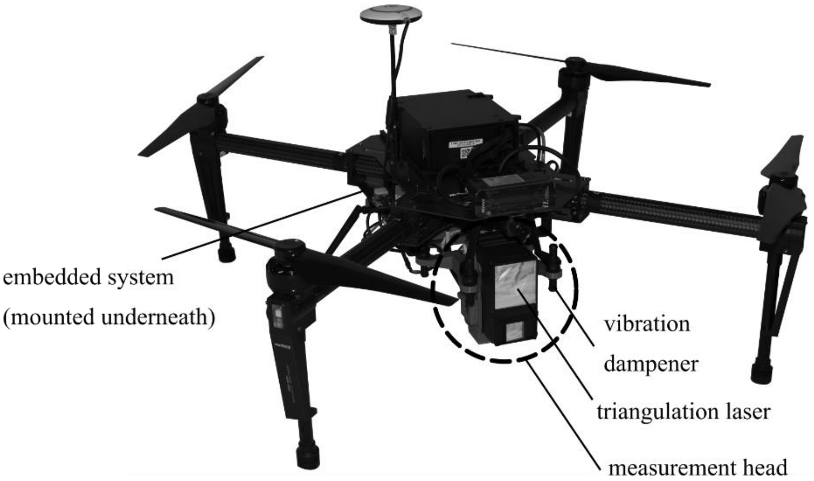

Figure 4. Prototype of mobile sensing platform for vibration analysis.

As already stated in section 3, preserving the phase of all signals is essential to make addition of signals in the time domain possible. Regarding the measurement, this means that the jitter of all signals has to be minimized and thus an embedded system with a CPU and a field-programmable gate array (FPGA) was used as a measurement device to enable hardware-parallelized sensor readings. Two angular rate sensors, one accelerometer and a laser displacement sensor have been used. All sensors are combined as a measurement head with a stiff encasing, ensuring that no change in position between sensors can occur. A vibration dampener is applied between the UAV and the measurement head that aims at decoupling it from higher frequency modes originating in the UAVs motors and rotors. Experiments were made with a program implemented with LabVIEW for Embedded Applications, consisting of a real time application running on the embedded system communicating with a host application on a computer via WLAN.

The prototype has been deployed to identify the fundamental frequency of the Timber Tower, a 1.5 MW wind turbine located in Hannover, Germany with a hub height of 100 m. Two measurements were made on the northwest and west side of the tower, each approximately aligned with the wind direction at a height of 66 m (2/3 tower height). Across both measurements the average wind speed was 10 km/h and the average temperature 15 °C. All measured signals were filtered with multiple bandpass IIR filters of Butterworth type between 0.1 Hz to 200 Hz and processed as described in section 3. The Fig. 5 shows the amplitude spectra of the measured distance, the displacement of the UAV in x-direction and the structural response as calculated from eq. (6) in the range from 0 - 1 Hz.

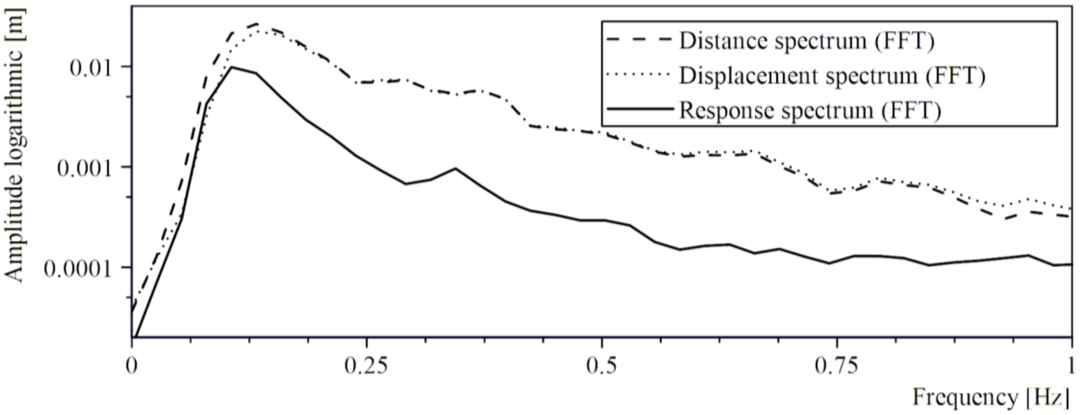

Figure 5. Amplitude spectra of measured distance (dashed line), UAV displacement (dotted line) and the response (solid line) from northwest side measurement of Timber Tower.

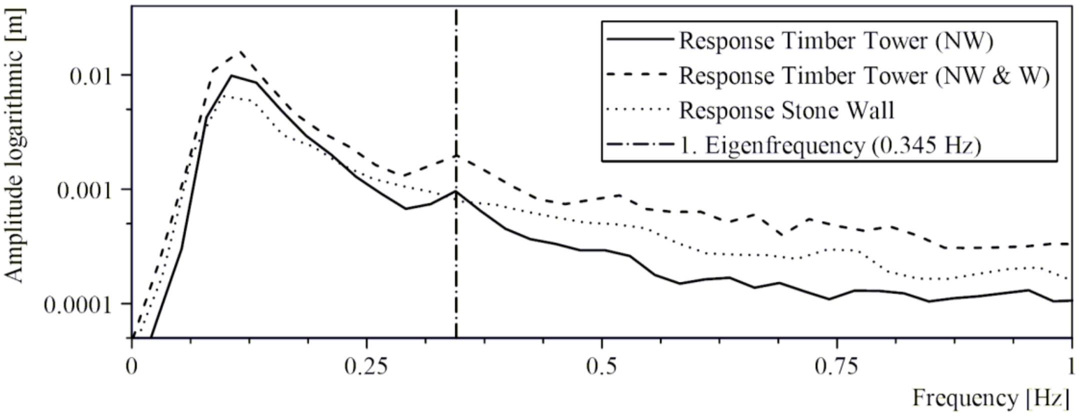

Figure 6. Response spectra obtained from measurements of the Timber Tower at his northwest side (solid line), combined northwest and west side (dashed line), measurement of a reference structure (stone wall) (dotted line) and the estimated first eigenfrequency of the Timber Tower (dash-dotted line).

The spectra were calculated using FFT with Hanning Windows applied prior to the transformation. The first large peak occurring at about 0.13 Hz is not an eigenfrequency of the structure but the unfiltered remaining power of UAV movements occurring at low frequencies and its position depends solely on the filter frequency, in this case 0.1 Hz, as well as the filter type and order. It can be seen that the spectra of distance and displacement are almost identical between 0.2 Hz and about 0.9 Hz. In the response spectrum a peak at 0.345 Hz can be identified, which is not contained in the displacement of the drone and thus must be an eigenfrequency of the structure. It is not possible to identify the eigenfrequency in the distance spectrum, proving that it is necessary to compensate the UAV movement in the distance measurement. In Fig. 6 the response spectra obtained from three experiments are shown, which were scaled based on the measurement time to make them comparable. The dashed line shows the response spectrum of a combined measurement from northwest and west side, which was obtained by appending both measurements in the time domain to increase resolution in the frequency domain and the dotted line shows the behavior of a structure with almost no vibrations (stone wall) as reference, where the pure drone dynamics are recorded with the single peak at 0.13 Hz . With this, the first eigenfrequency of the Timber Tower was estimated at 0.345 Hz. In Feldmann et al. (2016) the first eigenfrequency of the Timber Tower was given at 0.33 Hz as an average of both horizontal eigenfrequencies. The difference might be due to errors in either of the measurements, different structural behavior dependent on temperature, different control or orientation of the turbine or a shift in stiffness of the tower over the course of multiple years.

5 CONCLUSION AND OUTLOOK

This research shows that it is possible to perform vibration measurements at structural components using optical distance sensors that are mounted on a mobile platform, like a quadcopter-based drone. The vibrations of the mobile sensing platform are much stronger compared to the vibration of the structure. The advantages of this method are that the sensor setup for vibration measurements are simplified and can be automated by a flight-path planning of the drone. So the whole structure can be measured with a dense mesh of measuring points, so-called Degrees of Freedom (DOF). Developments in the direction of increased flight times, will enhance the spatial resolution. It is also possible to measure a number of structures that are located closely together, like in a wind park. The drone can automatically fly and measure at each single wind turbine. Using this technology, a whole wind park can be scanned on a regular basis, without the need of permanent installed sensors. This data can be used for inspection planning and damage detection as an indicator for irregular change of the structural dynamic behavior. Further investigations will be done to control a collective of drones measuring simultaneously and time synchronized at multiple positions to obtain the mode shapes of a structure. By also measuring at detached positions, it is possible to record the excitation like the ground shaking during a seismic event.

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