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Aerosense: Long-Range Bluetooth Wireless Sensor Node for Aerodynamic Monitoring on Wind Turbine Blades

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Abstract. Predictive maintenance and structural health monitoring are challenging and promising research fields today. In particular, cost-effective and long-term monitoring of wind turbines has been proven to be one of the key elements to successfully increase their efficiency. Accurate numerical modeling and real-time control-in-the-loop play an increasingly prominent role in understanding and optimizing blade aerodynamic and acoustic performances. A non-intrusive and modular measurement system is a prerequisite for long-term measurement campaigns in existing and future wind turbines. Current methods of performing aerodynamic and acoustic field measurements are cumbersome and expensive, leading to a shortage of aerodynamic and acoustic datasets on operating wind turbines. This paper demonstrates the ability of the new Aerosense system to operate successfully in the field. Aerosense is a long-lasting battery-operated and flexible wireless sensor node that can directly measure aerodynamic and acoustic effects on wind turbine blades. It consists of an array of state-of-the-art Micro-Electro-Mechanical Systems (MEMS) sensors, including 40 barometers and 10 microphones, combined with an ultra low power system-on-chip with wireless transmission over Bluetooth 5.1. Experimental results demonstrate the possibility of continuously acquiring data for up to four months on a single lithium battery of 8.7 Ah, featuring an absolute accuracy of 10 Pa and an audio bandwidth of 6 kHz.

1. Introduction

Wind turbine rotor blades are becoming larger and more elastic and thus it is becoming more and more important for engineers to rely on numerical models and simulations that reproduce real environmental conditions [1]. Measuring and understanding their aerodynamic and acoustic performance are essential for optimizing wind turbine efficiency, for example by detecting and classifying leading edge erosion and thus optimizing cleaning or planning repair strategies [2]. Moreover, detecting amplitude modulation helps to minimize shut-downs due to noise emissions [3].

Publicly available datasets of in-field aerodynamic and aeroacoustic measurements are needed to develop and validate models and simulations. However, acquiring data from operating wind turbines on towers up to 260 m high is a challenging practical task, and it usually requires large efforts and costs [4, 5, 6]. Indeed, they often require custom-made rotor blades with embedded sensors [4, 5, 6].

Non-intrusively measuring aerodynamic and acoustic data with minimal aerodynamic influence on blades is still an open challenge - the limitations for the form factor, power consumption and necessary data bandwidth require a highly optimized Internet of Things (IoT) system. Recently IoT wireless devices have been used more and more for Structural Health Monitoring (SHM) to detect anomalies early on [7]. Moreover, in-field monitoring using distributed systems has also been investigated and deployed in previous publications [8, 9, 10].

Although previous studies [11, 7] demonstrated the potential of using inexpensive MEMS (Micro-ElectroMechanical Systems) and integrated circuits (ICs) for SHM applications, no MEMS arrays of heterogeneous set of sensors are present in the literature, nor in commercial products, for in-field aerodynamic and aeroacoustic analysis on wind turbines. Arrays of MEMS barometers have already been investigated in several other case studies, where clusters of pressure elements have been embedded into surfaces, including airplane wings [12] and cars [13].

In general, the aforementioned work show that MEMS sensors can be used to acquire aerodynamic and aeroacoustic measurements on surfaces, but they do not address the wireless communication and power consumption challenges and requirements of continuous and long term monitoring [14]. In previous works, few examples of wireless platforms installed on wind turbines can be found [15, 7, 16]. These mainly consider vibration measurements [7, 17] for structural damage rather than proposing a device capable of acquiring aerodynamic data directly on the rotor blades. In these scenarios, the system has to handle data streams in the range of 5 kbps, while for aerodynamic analysis, a throughput larger than 1 Mbps is a fundamental requisite [18]. The additional data collected by arrays of barometers and microphones is crucial for wind turbine modelling, but on the other hand, it poses major challenges in the design of energy-efficient and long-lasting IoT devices.

In the Aerosense project, a novel wireless sensor node with a modular architecture to acquire data from 40 different MEMS pressure sensors and 10 microphones is therefore being developed. The design of the proposed node allows streaming of all the sensors in a wireless manner. To the best of our knowledge, Aerosense is the first low power, MEMS-based, and wireless sensor node designed for aerodynamic and aeroacoustic analysis on wind turbine blades. Moreover, it is supporting heterogeneous high-frequency MEMS sensors that are capable to provide long term and precise acquisitions.

Recent previous works describe the initial design and short-term wind tunnel functional tests of the Aerosense system [19, 18]. The main contributions of this paper are summarized as follows: (i) description of the general architecture of the Aerosense system designed to enable *in-situ* long-term monitoring of heterogeneous and accurate measurement on wind turbines; (ii) demonstration of the Aerosense system for long-term monitoring of wind turbine blades in the field.

2. Aerosense: Architecture

In this section, the architecture of Aerosense is presented. Figure 1 shows the high-level functionality and an intended deployment of the Aerosense system, together with its position on the blade. The power management part consists of a rechargeable battery with 32 Wh (8.7 Ah), which allow the sensor to work for up to four months at 8% duty cycle. To achieve this result, all the hardware and firmware has been designed to satisfy the project requirements at the lowest energy cost. Moreover, all the electronic is embedded in a thin flexible housing, which provides waterproofing and protection from the environment. In-depth analysis of the electronic design and sensor selection is available in our previous publicatiosn [18, 19].

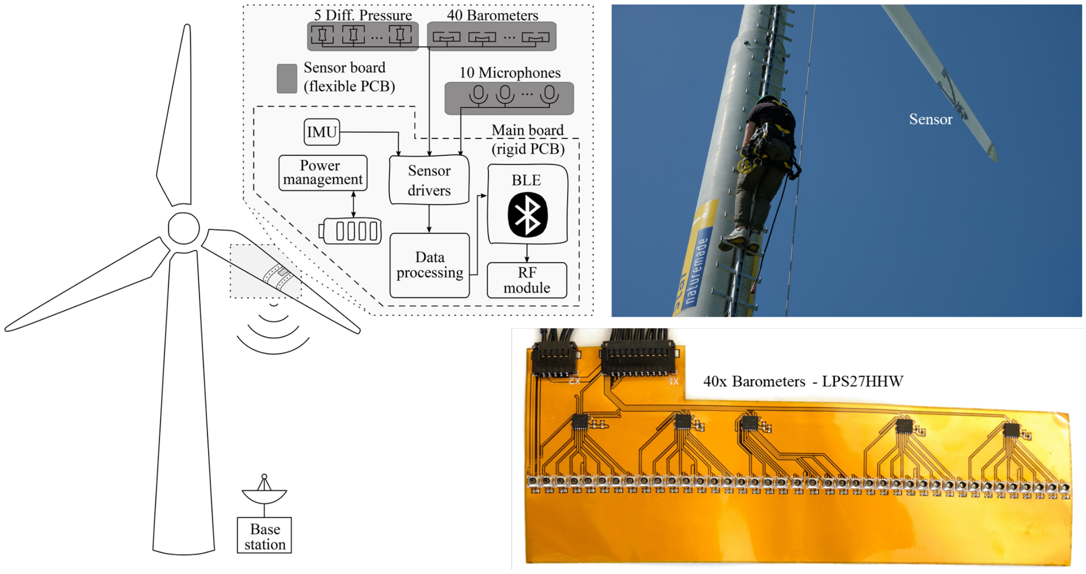

Figure 1: Wireless sensor node overview (left), measurement system installed in the field (top right) [20], picture of the flexible printed circuit board hosting 40 barometers (bottom right)

2.1. General electronics architecture

The proposed wireless sensor node features arrays of pressure and acoustic MEMS sensors and an Inertial Measurement Unit (IMU) coupled with long-range Bluetooth Low Energy 5.1 (BLE) communication to achieve in-field precise and long-term data collection, as shown in Figure 1. The hardware design is heavily optimized for power, achieving 133 mW of power consumption in active mode. In particular, it is meant for installation for a wide range of application scenarios, featuring a modular architecture with up to 40 barometers and 10 microphones, plus five differential pressure sensors. As presented in Fig. 1, each specific cluster of MEMS element is built upon a flexible printed circuit board, which is interchangeable and inter-operable with others. Differential elements are considered for future developments, such as automatic calibration and validation for long term installations. Thus, they are not considered in this paper in the experimental section and for the battery estimation. Moreover, with one single sensor node, it is possible to cover blades with a chord length up to 1 m, but for larger installations a combination of sensor nodes will be required.

The low power BLE System-on-Chip (SoC) employs a 20 dBm power amplifier to have both a long-range (up to 275 m) and a high energy efficiency, coupled with ~ 1 $Mbps$ bandwidth to stream all the collected data directly to the base station at the tower bottom.

The core of the Aerosense sensor node is built upon an ARM Cortex MCU (Micro Controller Unit), the Texas Instruments CC2652P. It features an integrated power amplifier enabling long-range wireless links and the possibility to handle the multi-Mbps data flow. Moreover, the CC2652P is designed for energy efficiency when reading out sensors, hosting a Sensor Controller (SC), which enables the use of one line of SPI and I2C at only 30 μA. The CC2652P encompasses a 48-MHz ARM Cortex-M4F processor, with 352 kB in-system programmable flash and 88 kB SRAM.

2.2. Barometers

Table 1 reports the aerodynamic parameters required for a reference 5 MW wind turbine, which define the working range and the accuracy for selected sensors. The pressure distribution around the rotor blade is measured using piezoresistive MEMS water-resistant LPS27HHW

Table 1: Orders of magnitude of aerodynamic and acoustic parameters based on the 5 MW reference NREL wind turbine, used to select pressure sensors and microphones.

	Parameter	**Accuracy**	**Range**
	diameter rotor		126 m
	rated wind speed		40 m s^{-1}
	rate rotational speed		12 rpm
mid-span	rated apparent wind speed		40 m s^{-1}
	average dynamic pressure	1 Cp	1000 Pa
	peak dynamic pressure	5 Cp	6000 Pa
	accuracy	1% of 1 Cp	110 Pa
tip	rated apparent wind speed		80 m s^{-1}
	average dynamic pressure	1 Cp	4000 Pa
	peak dynamic pressure	5 Cp	20 500 Pa
	accuracy	1% of 1 Cp	140 Pa
noise	dynamic range		50 dB to 130 dB
	frequency range		100 Hz to 5000 Hz

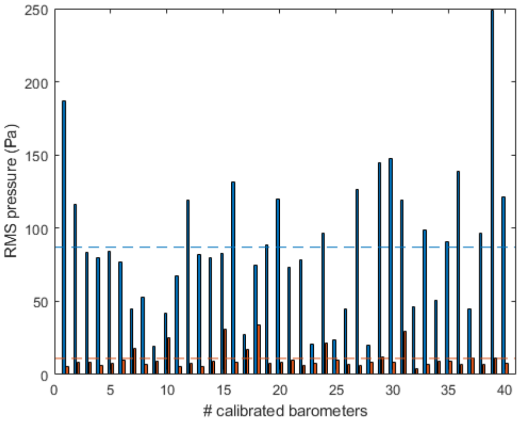

Figure 2: Accuracy obtained before (in blue) and after calibration (in orange) on the 40 individual barometers of our wireless sensor node. The average RMSE values are indicated with the horizontal dashed lines.

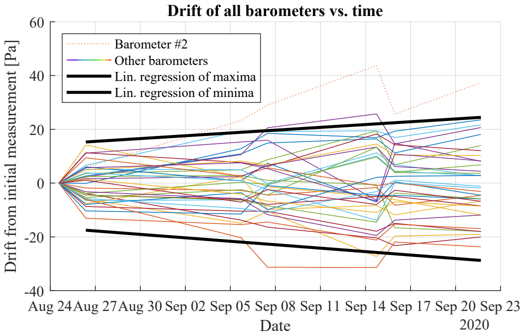

Figure 3: The mean-adjusted and zeroed pressure readings of 40 barometers. Barometer #2 was classified as an outlier.

from STMicroelectronics, which include a temperature sensor to enable custom and on-site calibrations. They can measure from 260 hPa to 1260 hPa absolute pressure range, covering the range for wind turbine monitoring (as shown in Table 1), at a frequency of 100 Hz, providing 500 measurement points during one rotation of the rotor. The sensors feature an absolute pressure accuracy of ±50 Pa, a relative accuracy of ±2.5 Pa and a low current consumption of 4 µA. If we want to obtain a 1% accuracy according to our requirements in Table 1, an absolute accuracy of 10 Pa should be achieved for the full operating range of the wind turbine, including in extreme conditions, thus requiring dedicated calibrations of the barometers. The barometers were calibrated in a dedicated chamber at EMPA, the Swiss Federal Laboratories for Materials

Science and Technology, during 36 hours, resulting in about 30 000 measurement points for a pressure range from 800 hPa to 1100 hPa and for a temperature range from −20 °C to 50 °C. A second-order surface fitting was applied first on the measured temperature T_{meas} to obtain the calibrated temperature T_{cal} using the measured non calibrated pressure P_{meas}:

$$T_{cal} = p_{t,00} + p_{t,10}P_{meas} + p_{t,01}T_{meas} + p_{t,20}P_{meas}^2 + p_{t,02}T_{meas}^2 + p_{t,11}T_{meas}P_{meas} \quad , \tag{1}$$

where $p_{t,ij}$ are the coefficient of the second order polynomial fitting for the temperature. The pressure was then calibrated, P_{cal} using this calibrated temperature T_{cal}:

$$P_{cal} = p_{p,00} + p_{p,10}P_{meas} + p_{p,01}T_{cal} + p_{p,20}P_{meas}^2 + p_{p,02}T_{cal}^2 + p_{p,11}T_{cal}P_{meas} \quad , \tag{2}$$

where $p_{p,ij}$ are the coefficient of the second order polynomial fitting for the pressure. The results are shown in figure 2 for all individual 40 barometers. Prior to the calibration, the Root Mean Squared Error (RMSE) between the reference pressure, measured with a precision of 2 Pa, and the measured pressure value was of 87 Pa (blue dashed line in Figure 2). After the calibration, the RMSE went down to 11 Pa (orange dashed line in Figure 2). Thanks to this custom-made calibration, we were able to improve accuracy of the barometers by a factor of nearly eight.

Another drawback of the MEMS barometers compared to top-of-the-range sensors is the thermal drift. During one month, all barometers were therefore sampled thousands times under static and equally-distributed environmental conditions. The acquired values of each measurement series were then averaged to get one pressure state per sensor and day. For each date, the mean of all pressure readings was subtracted to accommodate for differences in ambient pressure. Then, in order to simulate a one-time offset calibration, all curves were zeroed with respect to the first day by subtracting the initial offset. The result can be seen in Figure 3. To quantify the drift over time, the largest and smallest pressure readings of each day was calculated, and two linear fits were done - one for the maximal and one for the minimal. They are drawn as black lines in Figure 3. By taking the difference of their y-intercepts, the "base" fluctuation inaccuracy of the pressure readings was calculated to be 31 Pa. Besides, the drift was calculated to be 0.77 Pa/day by subtracting the slopes of the linear fits, which corresponds to 280 Pa/year. Note that these values relate to pressure differences between two sensors. Therefore, assuming that the true pressure is the mean of all barometers, the drift was found to be equal to ± 140 Pa/year, which is slightly higher than the specifications of the barometers (100 Pa/year).

After assessing the theoretical accuracy of the sensor, the barometers were tested in the wind tunnel at Ecole Centrale de Lyon on a NACA 63-418 wing profile with a chord length of 12 cm and a span of 30 cm. Measurements were carried out for different wind speeds (from $12.5\,\mathrm{m\,s^{-1}}$ to $50\,\mathrm{m\,s^{-1}}$, $Re = 1 \times 10^5$ to 6.5×10^5) to simulate a variety of application scenarios. The Aerosense measurement system was tested for static angle of attacks from $-4°$ to $24°$. The barometers of the Aerosense measurement system were compared with 20 pressure points measured at mid-span by a Kulite KMPS-1-64 pressure scanner with an accuracy of about 2 Pa. Figure 4 shows results for a wind speed of $50\,\mathrm{m\,s^{-1}}$, similar to the wind speed at mid-span of a 5 MW wind turbine according to Table 1, with an ambient turbulence intensity of 8%, similar to in-field measurements, at four different angles of attack in a range where rotor blades operate. For all angles of attack, the barometer value agree well with the values from the reference flush pressure sensors, with a larger difference near the trailing edge. However, the Aerosense measurement system, comprising of a smooth flexible housing, has a thickness of 3 mm, slightly altering the shape of the airfoil characterized by a chord length of 12 cm. This difference explains the variation between the pressure values. However, on a multi MW wind turbine, the extra thickness of the wireless sensor node is expected to affect the pressure distribution negligibly.

This work has shown that the barometers, after careful calibration, can provide accurate pressure measurements on a static airfoil.

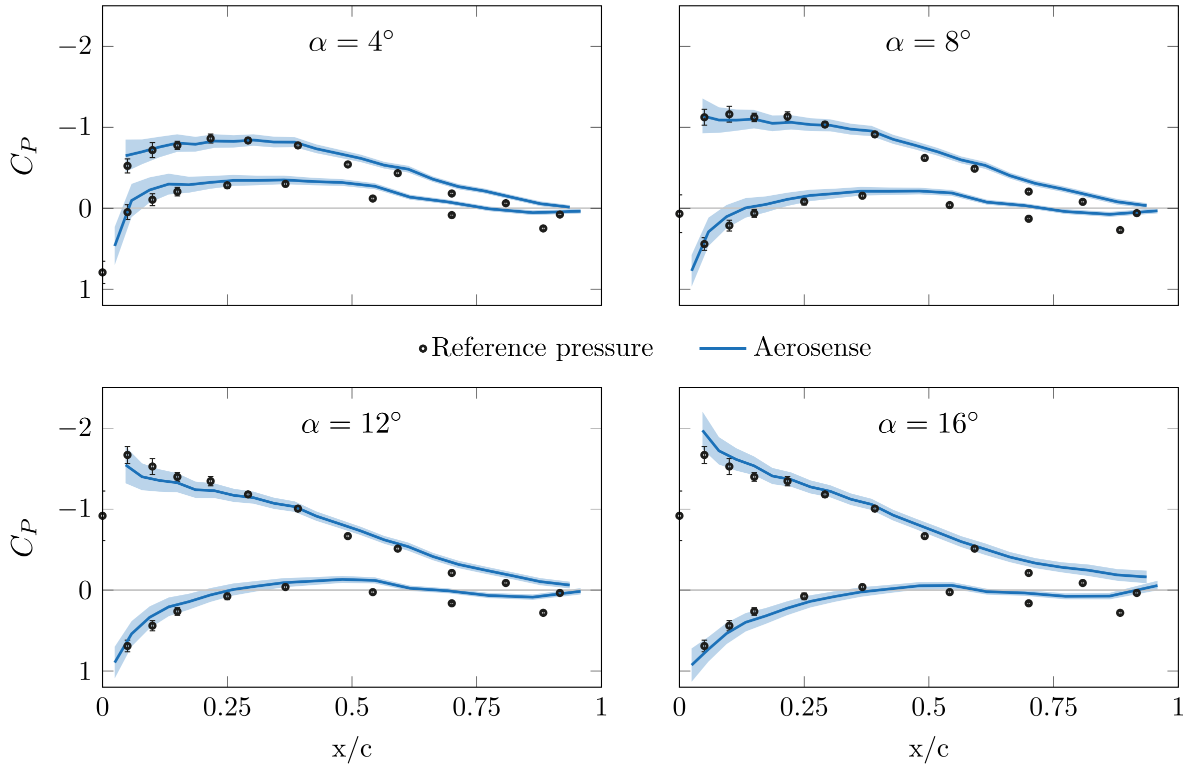

Figure 4: Average pressure coefficient distribution along the chord c for the Aerosense measurement system with 40 barometers at $U_\infty = 50\,\mathrm{m\,s^{-1}}$ with an ambient turbulence intensity of 8% at four different angles of attack. The shaded areas for the Aerosense system and the error bars for the reference pressure show the variations during 30 s using 2σ.

2.3. Microphones

The audio acquisition block is based on the Vesper VM2020, a differential analog piezoelectric MEMS microphone, which features power consumption of 825 µW and 152 dB SPL of acoustic overload point. It is dust and water resistant to IP57, essential for in-field measurements. In addition, it is coupled with two Texas Instruments ADS131M06 for the analog to digital conversion (ADC) at 16 kHz and zero-phase delay.

As they are embedded in a thin flexible housing, a small cavity above the microphones might affect the response of the microphones, therefore a calibration is applied using a loudspeaker and a reference sound receiver, as explained in [21].

The Aerosense microphones, tested in the wind tunnel at Ecole Centrale de Lyon w.r.t. 12 Brüel & Kjaer 4958 type microphones, detect correct amplitudes and frequencies until 4 kHz as seen in the Figure 5. Between 4 kHz to 6 kHz, the calibration compensates the underestimation of the amplitude of the pressure fluctuations, using the transfer function obtained between the Aerosense and the reference microphones, as presented in Figure 6.

3. Proof of concept on an operating wind turbine in the field

In order to test whether the chosen sensors are suited to measure aerodynamic phenomena and to demonstrate the functionality of the data acquisition system in the long-term with different types of sensors, the Aerosense system was mounted on a blade of an operating 6 kW Aventa AV-7 [20] wind turbine (see photo in Figure 1), located near Winterthur, Switzerland. The Aerosense system was positioned at 3/4 span on the 6 m long blade, where the chord length is

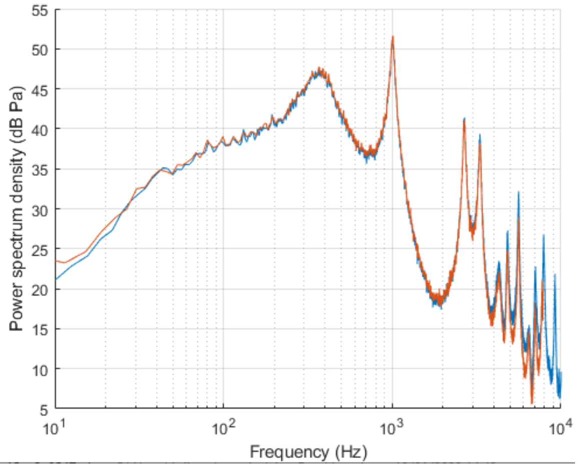

Figure 5: Power spectrum of the Aerosense microphone (in red) and of the reference microphone (in blue) recording sound emitted from a loudspeaker.

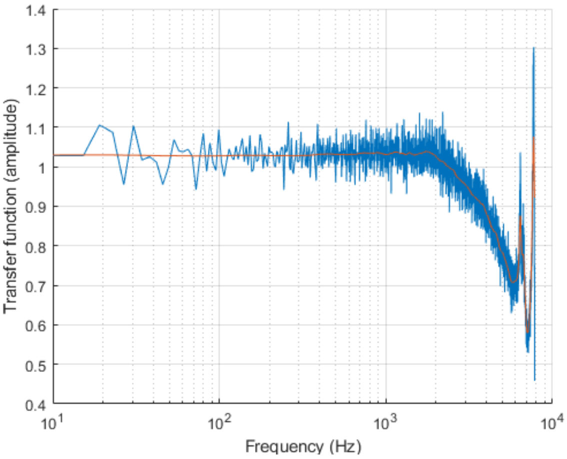

Figure 6: Transfer function between the Aerosense spectrum and the reference microphone. The red smoothed line is the transfer function used for calibration of the Aerosense microphone.

about 25 cm. The purpose of these tests was to demonstrate the feasibility of the installation and long-term acquisition of data from an operating wind turbine.

3.1. Aerodynamic measurement analysis

Pressure measurements were carried out over one day of operation. During this period, the blades were rotating at a constant speed, with a period of rotation of about 7 s. Barometer, microphone and IMU data were recorded simultaneously. The azimuth angle of the rotor blade was estimated by combining the accelerometer, gyroscope and magnetometer measurements using the `ahrsfilter` function from MATLAB. As all measurements were recorded using the same time clock, it was possible to convert time-resolved signals of barometers and microphones to phase-resolved signals. The measurements during this two minute period, with about 20 rotations, are shown in figure 7 vs. blade azimuth position. With a relatively low wind speed, the pressure varies more than 200 hPa during the measurement window, presented in the upper plot for two positions of the barometers, at the leading edge and at about 10% of the chord on the suction side. The large variations of pressure at the leading edge may indicate a change of angle of attack during one rotation of the blade. The low values on the suction side mean that a suction area is generated on the rotor blade. The peaks of pressure do not happen at exactly the same azimuth position during two minute period, but they always occur in the same quadrant of the rotation.

The lower plot of Figure 7 shows the sound pressure level recorded by one of the microphones near the trailing edge on the suction side. The average level is about 75 dB, with larger variations when the pressure at the leading edge stays constant. The larger variations of noise might indicate the flow is partially detached near the trailing edge, implying that the blade is operating at a large angle of attack during more than half of the rotation. It corresponds to our previous observation on the creation of high suction areas, which are generated at high angles of attack, before complete stall.

These tests show that it is possible to retrieve pressure and noise measurements wirelessly from a rotating blade on a wind turbine using low-power MEMS sensors. The heterogeneity of the sensors bring valuable information about the local aerodynamic performance of the wind turbine.

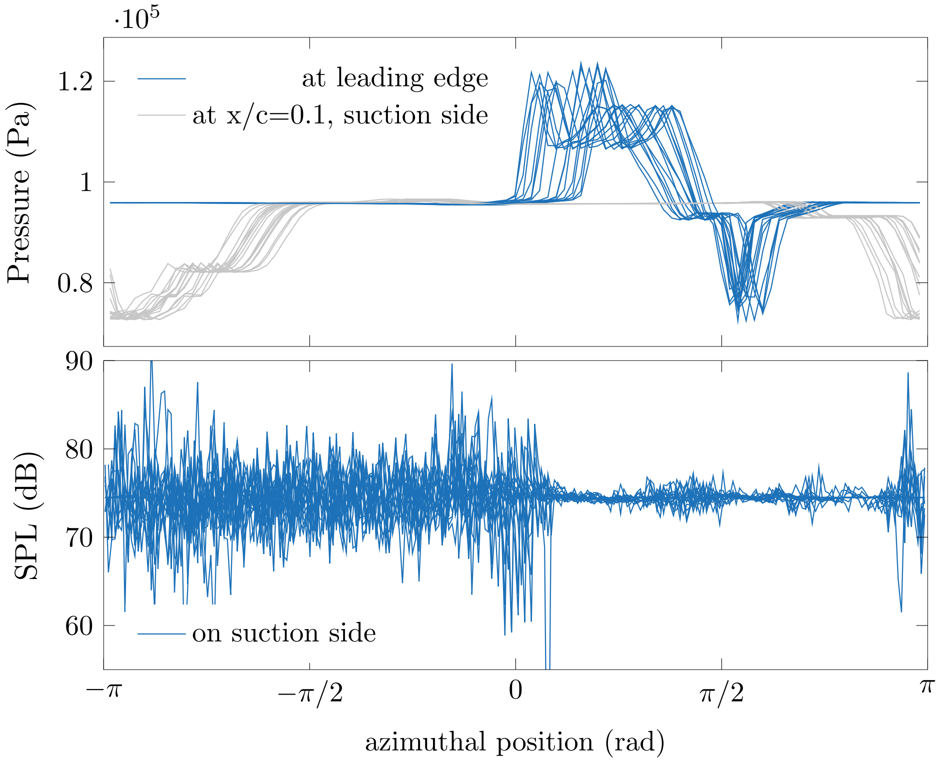

Figure 7: Two-minute averaged on-field measurements vs. azimuth position measured from the IMU. Top: Pressure signals of two barometers, at leading edge and at 10% of the chord on the suction side. Bottom: Microphone signal near the trailing edge on the suction side

Further tests are being prepared with an even more robust measurement system combined with SCADA and lidar measurements, as well with an automated measurement process where the data will be directly sent to a cloud-based server via a receiver in a base station, as described in more detail in [19].

3.2. System power analysis

To estimate the battery lifetime in various conditions and with different settings, each sub-block of our Aerosense device was measured. The power model was split into two operative modes: sleep and active. In active mode, the node is fully operative, collecting and simultaneously transmitting to the ground all the acquired data. Overall, on-board sensors generate a data flow of 3.45 $\mathrm{Mbit\,s^{-1}}$, which is above the maximum throughput supported by the BLE. Hence the remaining data is buffered on-board, and subsequently transferred to the base station. In sleep mode all the system is off - only an internal ultra low power real time clock (RTC) is active to wake up the electronics at the desired period. In this state the power consumption is minimal, reaching a value of 50 µW.

In active mode, the 40 barometers need 35.9 mW, in parallel with the IMU that requires only 4.3 mW. In addition, the whole signal processing related with microphones accounts for 31.7 mW, and the digital processing, together with buffering operations, require 61 mW. Then, in total the acquisition part needs 133 mW.

The power used by the wireless transmission is related to the distance between the base station and the Aerosense node mounted on the blade. Considering a scenario with multi-MW wind turbines, such as the 5 MW NREL reference turbine (see Table 1), this distance is variable in a range of 100 m; thus, we show here the average power consumption for each reported reference distance. At 25 m, the BLE uses 0.3 mW, while 275 m it increases of 350 times, reaching 107 mW. In the reported case study described in Section 3, the Aventa AV-7 is characterized by a hub height of 18 m, and a maximum ground-sensor distance of 25 m. In Figure 8, we show measurements of the Received Signal Strength Indicator (RSSI) and the resulting transmission power on the Aventa AV-7 turbine. Here, the aerodynamic analysis is executed for 25 min every 2 h, switching between active and sleep mode. In this condition the average power consumption is 11 mW with a total of 79 J per acquisition. On the other hand, in the worst case of a communication range above 275 m, these values increase respectively to 17 mW (203 mW in active mode) and 122 J.

In this work, we used a lithium battery with a capacity of 8.7 Ah, which contains enough energy to run the Aerosense system for 122 and 79 days, for the Aventa AV-7 wind turbine and the worst case respectively. Therefore the feasibility of using the Aerosense system for long-term aerodynamic and acoustic measurements in the field is demonstrated in this work. For future installations, we foresee the usage of a photovoltaic energy harvester, which will avoid a periodic battery replacement.

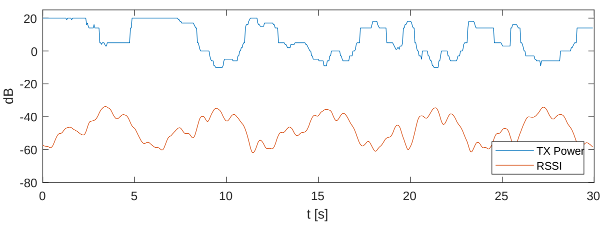

Figure 8: Performance of the transmission power control algorithm mounted on a 6 kW research wind turbine. The transmission power is adapted to the received signal strength (RSSI) that depends on the current location of the blade.

4. Conclusions

The Aerosense system is an ultra-low power, long-lasting and long-range Bluetooth wireless MEMS-based sensor node for aerodynamic and aeroacoustic measurements on wind turbines. This paper demonstrates the ability of the Aerosense system to operate successfully in the field.

We proved that our platform covers a wide range of application scenarios, in terms of size, rotor speed, and blade shape of wind turbines. Aerosense has been evaluated for functionality, range, and power consumption in a real installation. It has a low active power consumption of only 133 mW, and thanks to the optimized sleep mode, it can acquire data for over 120 days with a single battery charge. Experimental evaluations on the acquired data demonstrated that MEMS sensors are a valid solution to achieve absolute accuracy in the range of 10 Pa for pressure analysis, which is 1% of the full dynamic scale. Moreover, the paper showed that the microphone array has a linear behavior in the range between 50 Hz and 4 kHz, while between 4 kHz and 6 kHz a calibration is necessary.

Aerosense, to the best of our knowledge, is the first modular IoT solution to monitor and wirelessly collect aerodynamic and aeroacoustic information on operating wind turbines, combining high accuracy and long term battery lifetime.

Acknowledgments

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