Piezoelectric Patch Transducers: Can alternative sensors enhance bearing failure prediction?

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Abstract. This paper examines the applicability of piezoelectric patch transducers as condition monitoring sensors for the drive train of wind turbines. Three laboratory experiments are conducted to determine the sensor’s temperature stability, sensitivity toward electromagnetic interference and general ability to detect bearing damages. The sensors show little deviation under thermal influence in a tested temperature range between \(-40^\circ C\) and \(+80^\circ C\). Although they react to electromagnetic interference, the disturbance signal is predominated by the damage signal. Proper shielding is yet recommended to fully eliminate electromagnetic interference. An example of shielding is given through the use of mu-metal. In direct comparison of bearing fault detection capability to a state-of-the-art accelerometer, the patch transducer performs slightly worse in matters of signal-to-noise-ratio. However, when excited by small damage impulses, it yields good signal depth and output. Altogether, the sensor shows fundamental applicability as a condition monitoring sensor in all experiments, though further optimization seems feasible and worthwhile.

1. Introduction
Wind energy has been on the rise for several decades [1], starting as a dark horse between well-established conventional energy sources, it gradually emerged as the energy sector with the second largest growth in terms of annually installed capacity, aggregating a total capacity of 539 GW installed worldwide as of 2017 [2].

In the first years of distinct growth, namely the 1990s and early 2000s, condition monitoring was not very well known in the wind industry, but when increasingly more turbines became affected by substantial damages, insurers called out for a supervising system to predict upcoming faults [3]. DNV GL (at the time still under the name of Germanischer Lloyd) belonged to the first to attend to the postulation by releasing the first edition of their condition monitoring guideline [4]. Vibrational analysis has since evolved into the most known condition monitoring technique for failure prediction of the drive train [5] using accelerometers to gain high-frequency oscillations. But with the enormous growth of wind turbines – particularly in offshore turbine design – gearboxes have to adapt in terms of size and concept to meet the demands. The overall system’s stiffness and damping continuously increase, making it significantly more complex to retrieve low-energy vibrations emitted by incipient faults. While evaluation algorithms have been subject to optimization already, e.g. [6] and [7], the next step is to put further effort into the enhancement of accelerometers – or to look for alternatives. Such an alternative should be a step toward remote monitoring, i.e. a sensor, that can be both, self-sustained and applicable...
in difficult-to-access locations [8], while at the same time able to detect faults at least as good as state-of-the-art accelerometers.

In this paper, such an alternative in the form of a piezoelectric patch transducer is examined. It is neither a new technology, nor is it novel in the wind energy sector [9], [10], nevertheless, it has not yet been used as a sensor for condition monitoring of the drive train, even though it holds great advantages over accelerometers, such as lower cost, smaller design size, and the possibility of utilization as an energy harvesting micro-generator for wireless sensor nodes [11]. Its size and energy harvesting capabilities predestine it for the integration into assembly groups [12] or onto rotary devices, where wiring is impossible and self-sufficiency becomes essential. One such mounting position could be inside the gear, thus reducing signal paths between the damage impulse’s point of origin and the sensor, as well as minimizing the number of gaps that, referring to [13], are largely responsible for damping of structure-borne sound. An ambitious goal like this raises questions in matters of temperature stability, sensitivity toward electromagnetic interference, and power output from strains and vibration of monitored gear components.

This paper aims to answer some of these questions.

Section 2 pictures three different experiments for temperature stability, electromagnetic interference, and damage detection of bearing faults, whose results are presented and discussed in section 3. The paper closes with a conclusion in section 4.

2. Methods and experimental setup

The piezoelectric patch transducer (PPT) chosen for this project is the DuraAct P-867.A15 [14] by PI Ceramic GmbH, containing a PIC255-ceramic and two collecting electrodes embedded in a kapton coating. The sensor withstands severe bending moments and proves to be flexible and robust [15], two crucial characteristics for the application in a wind turbine drive.

The analysis of the piezoelectric patch transducer is accomplished in three stages. These contain a temperature test, an electromagnetic interference test, and finally, a direct comparison of the transducer with three types of accelerometers on a bearing test bench, though only one of which is presented in this paper.

2.1. Thermal influence

Literature research revealed several publications that attend to temperature effects on different piezoceramics. While these ceramics show quite diverse results, two important conclusions can be drawn from the inquiry. First, adhesive bonding indicates significant influence on the outcome, if an adhesive with too low glass transition temperature is utilized [9], [16], and second, the piezoceramic’s (PIC255) electromechanical energy conversion is scarcely affected by temperature changes in the range of −40 °C to +150 °C [17]. To incorporate these findings and at the same time meet the projects aims and budget, much attention has been paid to the conception and development of a test bench. Its functions should contain the possibility of varying the sensors elongation, remotely controlled excitation, small design size and withstanding the test temperatures. A suitable adhesive was found in DELO-DUOPOX® SJ8665 with a glass transition temperature of 126 °C.

Figure 1 shows the testbench and schematically describes its function. A thin steel sheet with the bonded PPT is periodically excited by a motor with a flange connected crank. After excitation the motor can be stopped to enable the damped oscillation to settle. Two PT-100 surface temperature probes (four-wire system) measure the test bench’s momentary thermal value. Tests are not conducted before the target value of the experimental stage is sufficiently obtained (±5 %). The PPT’s output is monitored by a measurement module, which allows voltage input as well as charge input.
Thermal testing is performed in a temperature cabinet with extreme temperatures set to $-40^\circ C$ and $+80^\circ C$, respectively. These values were determined to meet the requirements of cold and hot climate turbines [18] as well as maximum gear oil temperature [19] to investigate frame conditions for an integration into the gear. Temperature steps were set to 30 K, running through a full cycle, starting with cooling from $+20^\circ C$.

Due to the necessity of adhesive bonding of the PPT to a steel sheet, a composite is created, which itself significantly reacts to thermal variation, resulting in an undesirable bending line of the specimen. Compensation is essential to draw a reliable conclusion of the test.

![Temperature test bench](image1.png)

Figure 1: Temperature test bench; left: CAD model of the test bench, right: schematic functional description

2.2. Electromagnetic interference

The second stage of testing the PPT targets electromagnetic interference (EMI). Problems with EMI were detected during the execution of the primary direct comparison tests with accelerometers. The motor’s frequency converter of the bearing test bench produces electromagnetic fields that could initially be found in all of the accelerometer’s and the PPT’s spectra. Issues occurred only during downtime and in the case of the accelerometers also at very low revolution speeds. Much effort went into the recognition of the cause and its troubleshooting. Finally, a combination of sensor, electromagnetically shielded cable, grounding, and equipotential bonding between measurement module and test bench, provided an accelerometer without EMI that further on is used as a reference. This reference accelerometer holds a sensitivity of $500 \text{ mV} / g$ and a mounted resonance frequency of 16 kHz. The PPT stays unshielded for the direct comparison tests (section 3.3), yet it only shows disturbance frequencies with an amplitude of around $50 \mu V$ during downtime. As

![Electromagnetic interference test setup](image2.png)

Figure 2: Electromagnetic interference test setup
soon as the sensor produces voltage output, all disturbances disappear in the noise. Still, EMI are existent in PPT and deserve further investigation, especially since the frequency generator is relatively far away from the sensor and thereby disturbances are expected to be very low.

To achieve in-depth knowledge of EMI in PPTs, another test bench is utilized (Figure 2). It is specifically designed to produce electromagnetic fields with varying frequencies. During the EMI tests the sensor is put into a coil’s area of electromagnetic influence. It is thereupon examined whether the field frequency can be found in the sensor’s spectrum. The signal is recorded without any mechanical oscillation, thus registering only EMI.

2.3. Direct comparison with accelerometers

In the third stage, the transducers are applied and analyzed on a bearing test bench (Figure 3) and directly compared to different accelerometers with varying specifications. The test bench allows the exchange of the bearings, thus making it possible to embed corrupt bearings. A pretensioned V-belt is attached to apply transverse force to the shaft and thereby increase the damage’s impulse. An electromagnetic powder brake is included into the setup to introduce a load (2 Nm) into the system and improve its smoothness. The rotational frequencies can be varied by the frequency converter and monitored via a light barrier. The set of corrupt bearings contains outer ring, inner ring, and rolling body damages as well as a combination of the three, furthermore, a heavily worn bearing and a reference bearing without fault, all of which are radial ball bearings of type 6004.

3. Results and discussion

3.1. Thermal influence

Steel sheet, adhesive, and sensor form a composite with different thermal expansion coefficients. Leaving the hardening temperature at +20 °C all three components aim toward different elongations that can only partly be met, leading to mechanical stress between the layers and resulting in bending of the composite (Figure 4(b)).
Two factors are key drivers for the patch transducer’s voltage output: elongation and frequency \[20\]. While the resonance of the composite and steel sheet can be deviated from the measurements (Figure 5(a)), elongation has to be calculated. This is conducted by a thermo-elasto-mechanically coupled computation. First, the composite’s characteristics and its curvature are established through classical laminate theory. Then, mechanical bending by the motor’s crank can be included. Since the composite covers only a part of the steel sheet, its bending lines (composite and non-composite) differ fundamentally. Both bending lines have to be combined to globally describe the bending. Figure 4(a) shows the laminate’s calculated effect during thermal and thermo-mechanical influence. Special attention should be paid to the difference in elongation of specimen under extremely low temperatures (blue) compared to their high temperature counterparts (red). Thus, low temperatures lead to negative excitation, reducing the steel sheets preset relative deflection, hence resulting in less relative elongation and less voltage output. The calculated elongation of the composite, and consequently the sensor, shows linear correlation with temperature, which has to be taken into account when analyzing the voltage output.

Under the simplifications of application well below the piezoelectric resonance and measurements with a steady voltage gradient, linear correlation between elongation and resonance toward voltage output is assumed \[21\]. Both influences, elongation and resonance, are converted to relative change from original temperature conditions (Figure 5(b)) and used as compensation for the voltage output (Figure 5(c)). Details of the calculation and further results can be found in \[22\].

The transducer’s peak voltage output showed significant variation throughout the experiment, but after compensation a relatively steady voltage signal remains within the whole temperature range. It can therefore be concluded that the piezoelectric patch transducer itself does not show notable thermal dependency within the tested temperature range. This insight coincides with the findings of Rupitsch and Ilg \[17\] that the piezoceramic’s energy conversion is hardly manipulated by temperature changes.

The signals alteration therefore derives from the thermo-elasto-mechanically coupled bending of the composite and steel sheet.
3.2. Electromagnetic interference
Several arbitrarily chosen frequencies are adjusted in the frequency generator while the sensor’s spectrum is analyzed. The magnetic field strength is set to four different values, the highest possible value, which is limited by the amplifier, two default values complying with the standard [23] (1 kA/m and 0.3 kA/m), and a relatively small value of 0.1 kA/m. All of the artificially generated frequencies can be found in the spectrum as well as the 50 Hz mains frequency and its harmonics (Figure 6(b)). It can be derived from Figure 6(a) that both parameters, magnetic field strength and frequency, have significant influence on the PPT’s signal. Increasing one of them leads to higher voltage. It shall be noted that with elevated frequencies only lesser field strengths can be induced (e.g. 1 kA/m can not be generated at 11137 Hz), however, due to the higher frequencies, more energy is put into the sensor, resulting in a higher interference signal.

Figure 6: Electromagnetically induced voltage signals as a function of (a) field strength at various frequencies and (b) frequency with a fixed field strength at $H = 0.3$ kA/m (full spectrum up to 12.000 Hz)
To reduce electromagnetic interference, experiments with electromagnetic shielding are conducted. A 1 mm thick sheet of mu-metal, an alloy of nickel and iron with a high level of magnetic permeability, is placed between coil and transducer. Due to its permeability the magnetic field lines are concentrated inside the metal and deviated from their original direction. With exception of exceedingly high field strengths (6.010 kA/m and 4.285 kA/m) all artificially induced fields are thoroughly shielded (Figure 7).

An alternative to this method of shielding is given by Fraunhofer Institute for Nondestructive Testing [9], who tested different sensor designs. An optimum arises in stacking conversely polarized piezoceramics on top of each other with a collector electrode between, thus creating self shielding.

### 3.3. Direct comparison with accelerometers

All bearings are measured at rotational frequencies between 0 and 1500 rpm by the accelerometer and the PPT simultaneously. The output is subsequently investigated through a run-up plot (Figure 8), delivering a first impression of the sensor’s signal. The accelerometer shows clear growth of voltage output with increasing rotational speed, while the PPT’s signal yields high voltages at low rotational speeds already, but does not significantly increase its signal strength at higher speeds. In Figure 9 this phenomenon is presented in detail. Calculated damage frequencies and rotational frequencies as well as their harmonics and sidebands are highlighted in color to enable fault diagnosis. Formulæ for these frequencies can be found in various publications throughout literature, e.g. [24] or [7]. All damages and their expected frequencies are listed in Table 1.

| frequency $f$ in Hz | rotations $z$ in rpm |
|---------------------|----------------------|
| 0                   | 120                  |
| 1                   | 110                  |
| 2                   | 100                  |
| 3                   | 90                   |
| 4                   | 80                   |
| 5                   | 70                   |
| 6                   | 60                   |
| 7                   | 50                   |
| 8                   | 40                   |
| 9                   | 30                   |
| 10                  | 20                   |
| 11                  | 10                   |

Figure 8: Run-up test of an inner ring bearing damage as measured by (a) an accelerometer with a sensitivity of 500 mV/g and mounted resonance of 16 kHz and (b) a piezoelectric patch transducer with a ceramic layer thickness of 500 µm.
Figure 9: Damage spectra of (a) an inner ring damage, (b) an outer ring damage and (c) a bearing with inner ring, outer ring, and rolling body damage, each at 200 and 1300 rpm as measured by an accelerometer with a sensitivity of 500 mV and mounted resonance of 16 kHz and a piezoelectric patch transducer with a ceramic layer thickness of 500 µm.

In case of Figure 9(a), a bearing with inner ring damage is presented. Here, the PPT shows advantages at low rotational speeds, where the inner ring damage frequency, its first harmonic and several sidebands can be identified. By increasing the rotational speed, the signal voltage rises, but the signal depth deteriorates. The damage frequency and its sidebands are still recognizable, though its first harmonic is lost. In contrast, the accelerometer produces lesser signals at low speeds with slightly inferior signal depth, but gains in terms of amplitude and
signal depth at high rotational speeds. The first harmonic and its sidebands are visible and the signal-to-noise-ratio is of high quality, thus facilitating a precise diagnosis.

As mentioned before, several different bearing damages are monitored, not all of which can be similarly well detected by the patch transducer. While inner ring and cage damages as well as the belt’s repetition rate are found in all spectra from 100 to 1500 rpm, the outer ring damage frequencies are not very distinct throughout the whole run-up (Figure 9(b)), whereas the accelerometer’s spectrum identifies clear signs of an outer ring damage. The rolling element damage (not shown in this publication) is neither present in the PPT’s signal nor in the accelerometer’s signal. It is assumed that the damage itself is not overrun, but instead excites the cage, which on the other hand can be spotted in all spectra of bearings with rolling element damage, i.e. in Figure 9(c).

Table 1: Damage types and their frequency calculations with number of balls \(n\), rotational frequency \(f_r\), ball diameter \(D_W\), pitch circle diameter \(D_T\) and contact angle \(\alpha\)

| bearing damage type                          | expected damage frequency                                                                 |
|---------------------------------------------|-------------------------------------------------------------------------------------------|
| outer ring damage                           | \(f_{or} = \frac{1}{2}nf_r \left(1 - \frac{D_W}{D_T}\cos \alpha \right)\)               |
| inner ring damage                           | \(f_{ir} = \frac{1}{2}nf_r \left(1 + \frac{D_W}{D_T}\cos \alpha \right)\)               |
| rolling body damage                         | \(f_{rb} = n\frac{D_T}{D_W} \left[1 - \left(\frac{D_W}{D_T}\cos \alpha \right)^2 \right]\) |
|                                            | \(f_{cage} = \frac{1}{2}n \left(1 - \frac{D_W}{D_T}\cos \alpha \right)\)               |

4. Conclusion and outlook
A distinct answer to the question stated in the title can not be given. The PPT clearly shows good signal quality at low rotational speeds when excited by low-energy impulses, even though the accelerometer’s signal depth is hardly inferior, merely its voltage lacks in amplitude. At higher rotational speeds and thus stronger impulses, the accelerometer excels the PPT in matters of amplitude, signal depth and signal-to-noise ratio.

This being said, a potential for future use in condition monitoring still remains, because what can be answered by this paper with certainty, is that a general usability of the sensor in detection of bearing defects is assured, though, high frequency tests have yet to be undertaken to determine the sensor’s ability of measuring in the range of gear components’ resonances. Moreover, experiments show that no significant thermal influence is distinguishable in the tested range of \(-40^\circ C\) to \(+80^\circ C\) and electromagnetic interference can be eliminated by proper shielding.

In contrast to accelerometers, which have been subject to research and development for more than half a century \[25\], early patents of patch transducers (as used in this project) only date back to the 1990s \[26\] and early 2000s \[27\]. Fraunhofer IZFP \[9\] showed, by developing a self-shielding design, that optimization of the transducer is possible and worthwhile. Furthermore, patch transducers have already been used as micro generators for self-sustaining sensor nodes, though additional effort will have to be made to determine the PPT’s possible energy output when applied in a wind turbine to eventually dimension a low-energy wireless sensor node.

It is the authors’ belief that piezoelectric patch transducers bear potential for the application as condition monitoring sensors of the drive train, though further research is necessary to enhance their competitiveness toward state-of-the-art accelerometers.
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