Title: Experimental assessment and validation of an oil ferrous wear debris sensors family for wind turbine gearboxes

Abstract: **Abstracts should contain no more than 250 words and each section is limited to 100 words**.

Purpose of this paper (*)	In this paper a complete experimental assessment of a family of oil ferrous wear debris sensor is performed. The family is comprised by the original sensor and its re-engineered evolution, capable of detecting both amount and size of wear debris particles trapped by the sensor and some predefined oil condition properties.
Design/methodology/approach (*)	In this work, the first step was to perform a design of experiments for the sensor validation. A specially defined test rig was implemented, and different ferrous wear debris was collected. For each sensor, it was decided to perform two different tests. The first test was called “void test”, where quantified amounts of debris were collided with the sensor without oil. The second one was a dynamic test, where the sensor was installed in the test rig and different amounts of wear debris were added at a constant rate. In addition, specific tests related with oil properties detection were studied.
Findings (*)	The results shows excellent correlation of the sensor output signal with the amount of wear debris, and a satisfactory detection of debris size in all ranges. Also, the dynamic test presented adequate representativeness, and sensors performed well in this scenario.
Research limitations/implications (if applicable)	
Practical implications (*)	This paper shows the practical implementation of this type of sensor, and the usual detection range and rate of detection for different debris size and quantities.
Social implications (if applicable)	
What is original/value of paper (*)	This work has a great utility for maintenance managers and equipment designers in order to fully understand the potential of this type of sensor and its suitability for the application required.

1. Introduction

Wind energy is considered one of the most promising renewable energy sources to help tackling climate change, and it has been growing at full pace in recent times. This fact has encouraged leading companies in the electric production sector to invest more and more on wind power generation.

However, this alternative energy presents some pending challenges related to implementation and maintenance, leading to economic profitability problems. As the equipment has been growing, both in size and in economic investment, reliability has become a critical parameter for asset managing strategies. Reliability is understood as the ability of a system to consistently perform its intended or required function or mission, on demand and without degradation or failure (Holmberg *et al.*, 2010). The vast majority of mechanical systems present tribology-related issues that are responsible of nearly 70% of efficiency loss events in mechanical equipment (Rabinowicz, 1995). For example, in the case of renewable wind energy production, current wind turbines present two main characteristics. Firstly, they are large machines where the service downtime is a very important cost to assume for maintenance purposes. Also, the maintenance operation is expensive, due to the remote location of the turbines, the expensive equipment required and safety procedures.

In the specific case of on-shore wind turbines, usually they present an estimated life-span of 20 years, and the maintenance costs of a new turbine will be very low at the beginning but as the turbine ages these costs increases, as shown in Table 1.

Table 1. Key figures for operation and maintenance cost for on-shore wind turbines (Sheng, 2013).

Failure rate	1,5 to 4 failure per year
Cost corrective maintenance 5th year	5-8 €/kW
Cost corrective maintenance 15th year	40-60 €/kW

As can be seen, there is a crucial interest in maintenance issues as the wind turbine ages. New ways of maintenance management have been developed along the years in this engineering sector, where condition-based maintenance has emerged as a very interesting trend.

All this facts have arisen the possibility of remote condition monitoring, especially in the case of wind turbine gearboxes (Sheng and Veers, 2011). In this case, machinery condition data is mainly acquired by the use of sensors specifically designed for each mechanical system, integrated in the machine structure and working remotely. Different sensing technologies have been developed for condition monitoring: vibration analysis, acoustic emissions, temperature monitoring, lubricant analysis, corrosion monitoring, ultrasonic and leaks and cracks detection (Holmberg *et al.*, 2010). But, the monitoring of different equipment cannot be developed without knowing the different boundary conditions of s the equipment. This also defines the adequacy of the different settings of the monitored system: sampling rate and conditions, performed tests, etc. (Errichello *et al.*, 2011)

Lubricant condition monitoring can detect a high percentage of efficiency loss causes in a mechanical system, thus has become a powerful tool for maintenance managers. In recent years a wide range of on-line sensors has been developed to help maintenance managers to get continuous data about the condition of the lubricated system, helping them to modify and adapt maintenance procedures along the life of the lubricated system. In general, there are different sources of lubrication failure comprised in three main phenomena: external contamination of oil, oil degradation and excessive wear associated with surfaces in contact (Rizvi, 2008). Obviously within each application, each of these events will be presented with different prevalence, so it is mandatory to adapt monitoring devices to the boundary conditions of the studied system.

In this case, a family of sensors designed to monitor ferrous wear debris in lubricating oil in a wind turbine gearbox has been experimentally validated. This work could help maintenance managers and wind turbine gearbox manufacturers in order to fully understand the potential of this type of sensor and its suitability for the application required.

2. Lubricating oil ferrous wear debris sensor
    a. Oil wear debris

The presence of wear debris in lubricating oil is inherent to its use. One of its main functions is to evacuate those particles from the sliding surfaces, in order to prevent more severe damage. The composition and size of typical wear debris in oil has been studied deeply, and depends on different parameters (Tucker *et al.*, 1999; Edmonds, Resner and Shkarlet, 2000). The construction material and coatings in turn define the composition of the wear debris, and its ability to be detected by sensors. On the other hand, particle size and quantity has been correlated with machine operation (Dempsey, 2001; Dempsey, Lewicki and Decker, 2004). Several studies have indicated that during common machine operation, wear debris is produced at a constant concentration and small size, typically in the range of 1–100 μm. But when abnormal wear begins, the debris concentration and size increases gradually with time until equipment failure, with bigger particles as large as 500–1000 μm. In **¡Error! No se encuentra el origen de la referencia.** an evolution diagram of this process is shown.

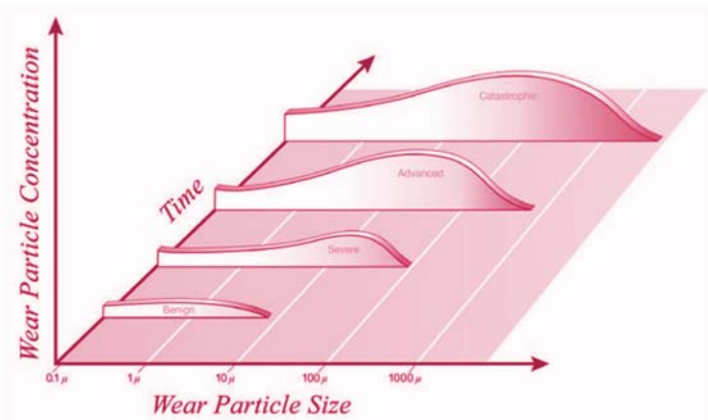

Figure 1: Typical distribution of wear debris size and evolution along machine life. Adapted from (Johnson, 2011).

The main conclusion that can be obtained from the graph is that it is possible to point a size range that can be considered the onset of severe wear and this is the usual objective of sensor technologies.

b. Sensing principle

Different techniques applied to the specific problem of gearbox wear debris measurement have been developed during the last years, mostly derived from another mechanical areas (Hunt, 1993). Optical counters, both laser and visible light-based, have been applied for particle size detection in mechanical equipment. On the other hand, several sensors based on electrical properties (dielectrical constant or Tan Delta) have been developed since the very beginning. The main problem with these sensors is that is not possible to distinguish between several phenomena that affect the wind turbine gearbox.

Furthermost, magnetic principles have been applied widely in different variations. Different magnetic properties have been studied: magnetic flux variation, magnetic pickup procedures, and magnetic inductive sensors. Other magnetic-related effects, such as Hall Effect (Chiou, Lee and Tsai, 1998) and Coulter principle (Du and Zhe, 2011) have been applied successfully. In some of these cases, even non-ferromagnetic particles can be detected (Dupuis, 2010).

In this work, the family of sensors studied has applied an optimization of magnetic flux principle. In this case, a permanent magnet attracts ferrous particles to the pulsed induction zone; an inductive coil within the sensor probe can differentiate both fine and coarse particles, since it alternately generates magnetic pulses and measures the strength of the debris' induced magnetic field.

3. Design of experiments

The general aim of this work was the validation of sensor performance with different sizes and amounts of ferromagnetic material, in order to simulate wear debris distributions ranging from an initial wear until the occurrence of a severe wear. This work could help to optimize wind turbine predictive maintenance purposes.

This work was divided in two main steps. The first phase comprised void tests, where the sensor was tested without any oil. In this part a precise characterization of the sensor response was made, studying sensitivity limits, degree of interference and reaction to other materials. In the second part, a characterization in common work conditions of the sensor was developed. In this case, the sensor was submerged in wind turbine gearbox oil and emulating common conditions in oil reservoir, by means of a dedicated test rig developed in-house.

a. Wear debris

A wide variety of wear debris was collected, trying to cover all wear processes developed in a wind turbine gearbox. Iron powder from different sizes was collected from Alfa Aesar (Alfa Aesar, 2016), with the size distribution shown in Table 2. Iron particles form is usually considered irregular, except in the case of #4 and #7, that they are considered spherical (marked with an E).

Table 2. Iron size distributions.

Number	Iron size distribution
1	<10 µm
2	<44 µm

3	125-250 µm
4	125-250 µm E
5	149-297 µm
6	250-315 µm
7	250-315 µm E
8	315-630 µm
9	1-2 mm
10	3,175 mm
11	2-12mm

In Figure 2 selected microscopic pictures of iron particles are shown.

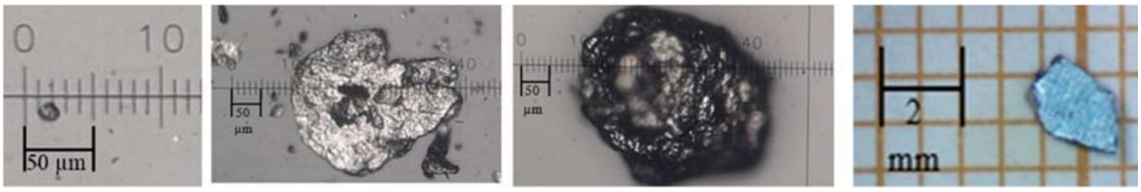

Figure 2: Microscopic pictures of the iron particles used: type #2 (left), type #6 (left-center), type #7 (right-center) and type #11 (right).

On the other side, copper particles in the range of 600-800 µm were collected and used to check the signal for non-ferrous materials.

b. Test rig designed

During the development of the test, a specific test rig was implemented. In this case, the design of this test rig considered a reduced amount of space and tried to simulate as carefully as possible the induced fluid movement into the oil reservoir.

Due to the relatively smooth movement in the wind turbine gearbox oil reservoir, a continuous movement of the oil was required but without producing any foaming processes. With the help of a commercial mixer, a test bench was developed as shown in Figure 3.

Figure 3. Experiment test rig, with the sensor installed and voltage meters to continuously control the results of the experiment.

c. Sensor specifications

As said before, a family of sensors was tested coming from Gill Sensors & Controls Ltd. (*Gill Sensors and Controls Ltd. website*, 2016) comprising different capabilities, as shown in Table 3.

Table 3. Sensor family specifications.

Sensor	A	B
Picture		
Supply voltage	4,5-32 VDC	5-32 VDC
Sample rate	10 Hz	10 Hz
Capabilities	Fine particle sensor Coarse particle sensor	Fine particle sensor Coarse particle sensor Oil condition/Temperature sensor
Sensor range output	Fine:2.25V-4.25V Coarse: 0.25V-4.25V	Fine: 1V-10V (calibratable) Coarse: 1V-10V (calibratable)

4. Results

Due to the great quantity of test involved, in every step of the results description will be shown at the same time for both sensors.

a. Void test

First, a void test was performed where controlled amounts of mass were added to the sensor and voltage was measured. In Figure 4 results for fine channel are presented and in Figure 5 results for coarse channel.

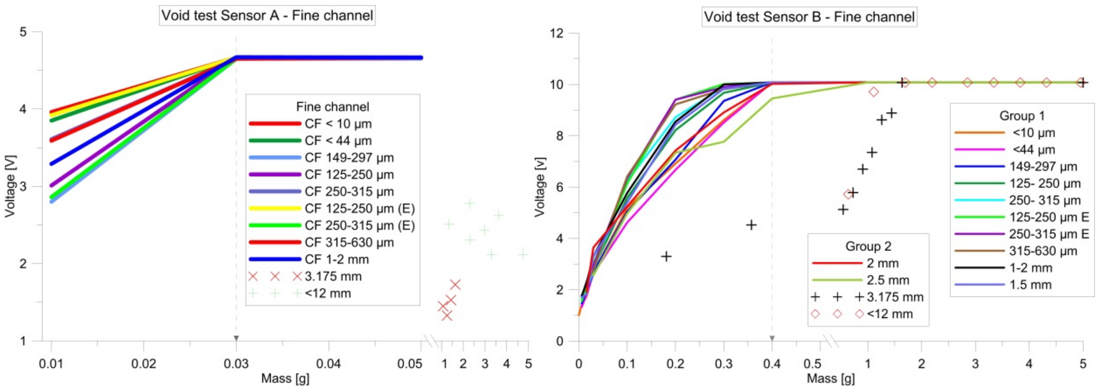

Figure 4. Results for the fine channel - void test of sensor A (left) and sensor B (right).

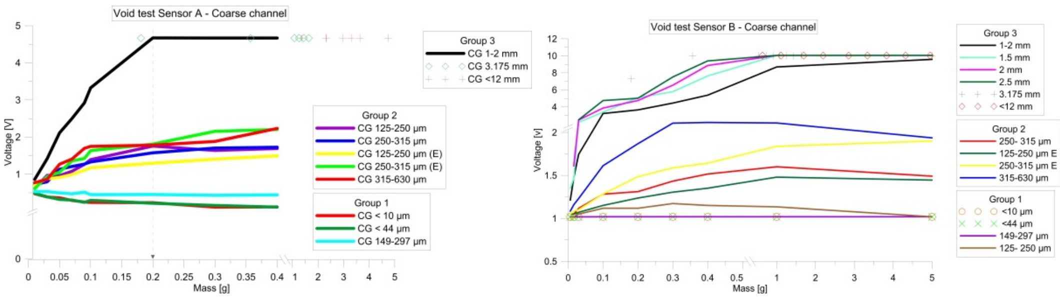

Figure 5. Results for the coarse channel - void test of sensor A (left) and sensor B (right).

These results showed different aspects to be mentioned. First of all, both sensors work in an accumulative trend, this means that a greater amount of particles trapped by the sensor results in an increased voltage signal. On the other hand, the difference in detection range between both sensors is remarkable. Sensor A is capable to detect amounts of particles up to 0.03 grams while sensor B detects up to an amount of 0.5 grams of iron particles.

The difference between sensor channels is also remarkable. In both cases is possible to detect the following trend: fine channel detected particles from a wide range of sizes, while coarse channel presented a performance divided in three groups of particle sizes: Group 1 presented no response for all the masses, while group 2 and group 3 presented increasing voltage rates depending of particle size.

In order to detect more precisely the particle size differentiation, an interference test was performed, where signal was compared against the mean particle size for the same mass added. In Figure 6 results are shown.

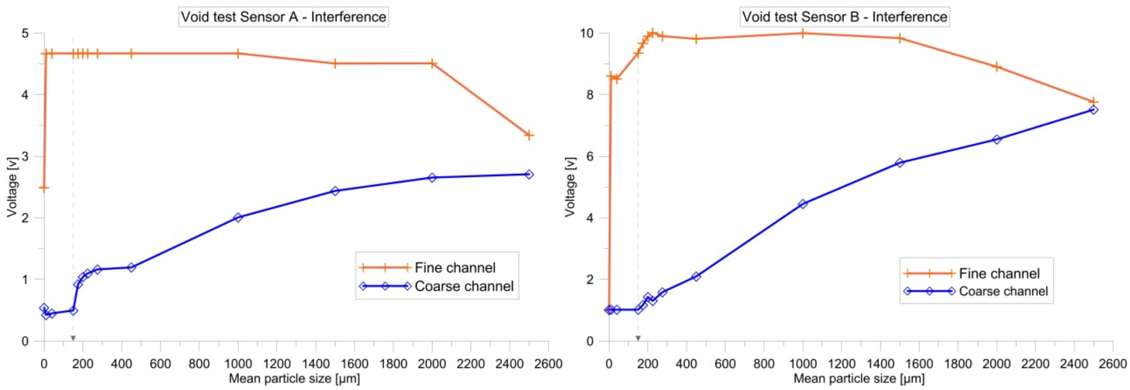

Figure 6. Results for the interference - void test of sensor A (left) and sensor B (right).

As can be seen in Figure 6, coarse channel started to react from a mean particle size of approximately 180 µm, while the fine sensor responded to all particle sizes. This phenomenon occurred for both sensors.

The last part of the void test included a non-ferrous particle test. These particles would not be trapped by the sensor, but the magnetic principle of the sensor would allow their detection. In this case, the sensor was attached to the particles deliberately. In Figure results are shown.

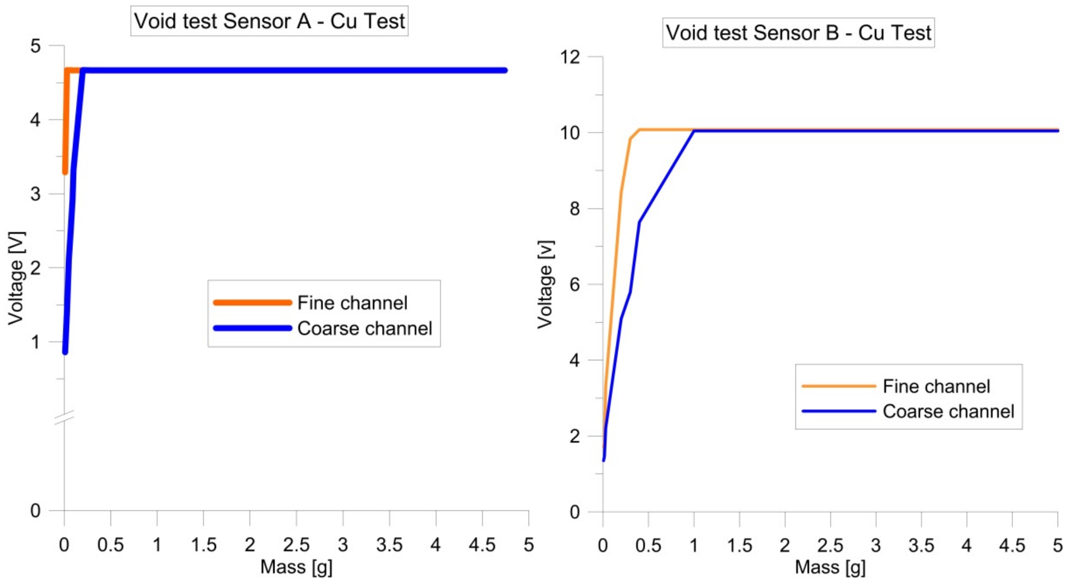

Figure 7. Results for copper - void test of sensor A (left) and sensor B (right).

The results pointed out that sensor also presented a response for copper particles, and satisfactorily detected their size.

b. Oil test

After the different test performed without oil, sensors were installed in the test bench. The oil test comprised the addition of fixed quantities of iron particles during stipulated amounts of time, as shown in Table 4.

Table 4. Oil test definition.

		Test								
		1	2	3	4	5	6	7	8	9
Particles		<10µm	<44 µm	149-297 µm	125-250 µm	250-315 µm	125-250 µm E	250-315 µm E	315-630 µm	1-2 mm
Sensor Tested		B	B	B	B	B	A/B	A/B	A/B	A/B
Steps (mass added g)	1	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
	2	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
	3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
	4	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
	5	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
	6	0,55	0,55	0,55	0,55	0,55	0,55	<0,55	0,55	0,55
	7	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55
	8	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55
	9	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55
	10	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55
	11	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15
	12	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15
	13	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15
	14	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15
	15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15	1,15
Total mass (g)		10	10	10	10	10	10	10	10	10

In Figure 8 the results for the fine channel in oil tests are shown, while in Figure 9 the results for coarse channel are shown.

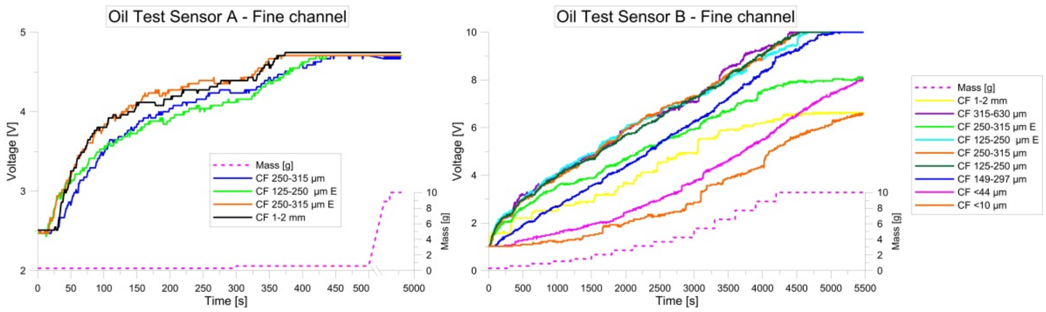

Figure 8. Results for the fine channel - oil test of sensor A (left) and sensor B (right).

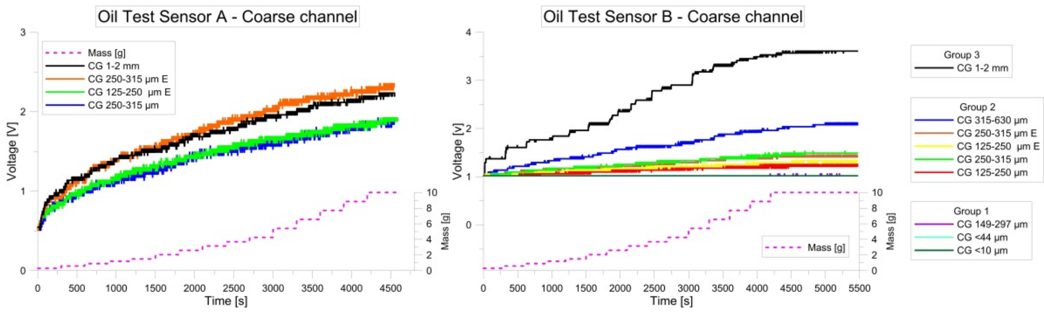

Figure 9. Results for the coarse channel – oil test of sensor A (left) and sensor B (right).

The results for the different oil test performed presented a good correlation with the results for the void test, in both sensors and channels trends. In the case of Sensor A, sensor signal was saturated very early in the test for the fine channel, while the performance of the sensor for every type of particles corresponded with their size. About Sensor B, it presents a good correlation with the mass added, especially in the range of 1-2mm particles. The sensor saturates the fine channel in the case of the finer particles. In order to understand better the results, the total mass captured by the sensor at the end of the test was measured, as shown in Table 5. In Figure 10 is shown an example of test end for both sensors.

Table 5. Results of mass trapped for every test.

Particles	Type	Sensor A		Sensor B	
		Mass [g]	%	Mass [g]	%
1	<10µm	-	-	4,162	41,62
2	<44 µm	-	-	4,398	43,98
3	149-297 µm	-	-	5,289	52,89
4	125-250 µm	-	-	4,115	41,15
5	250-315 µm	2,369	23,69	4,142	41,42
6	125-250 µm E	2,513	25,13	4,784	47,84
7	250-315 µm E	3,154	31,54	5,238	52,38
8	315-630 µm	2,204	22,04	4,704	47,04
9	1-2 mm	0,573	5,73	2,214	22,14

Figure 10. Image of mass trapped in the 1-2mm particles test for sensor A (left) and sensor B (right).

The results for mass retention presented a decreasing relation with particle size. The main hypothesis is that a greater particle size would sink and deposit faster than the smaller particles, thus escaping from the sensor magnetic field.

On the other hand, a difference between oil test and void test voltage values was detected for the same mass and particle size. Observing the final position of the particles attached to the sensor, it was detected that a part of them were attached to non-sensing surfaces, thus leading to an underestimation of wear debris particles.

5. Conclusions

In this article, an experimental assessment and validation of an oil ferrous wear debris sensors family for wind turbine gearboxes was performed. Different test were developed to assess the performance of these sensors based in magnetic flux detection.

Sensors performance was satisfactory, both in void and oil tests. According to sensor data, it was concluded that they worked as a mass detection sensor, that is, they increased its output value (voltage) depending on the mass trapped, independent of particle number. All sensors and channels responded favourably to all mass quantities. The interference test between channels allowed us to assess the size of the adhered particles, knowing the output voltages of both channels and relating them to the different average particle diameters.

A satisfactory performance of the sensors in oil test was observed, since they had a very similar performance to the void test results, this means that the oil did not represent an obstacle in the particle detection process.

Particle collection rates seemed constant up to the size of 1-2 mm. This was considered a consistent performance, since larger particles tend to settle down easily at the bottom of the system and it is increasingly difficult to find particles in suspension.

The detection capacity of the sensor must be a factor to take into account when placing it in the wind turbine gearbox. It is highly recommendable to use several specimens, placing them in different spaces, and being very careful with non-sensing surfaces in order to maximise sensor output.

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