Evaluation of the use of an electrical drive as a sensor for the detection of bearing damage

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Introduction

The most common mechanical faults in industrial processes are related to the bearing damage [1]. These are detected essentially by vibration analysis with different detection methods [2]. However, this solution may be expensive or requires a challenging mechanical construction depending on the number of used accelerometers and the kind of bearing. For this reason, investigations are made about the use of motor current signatures for the detection of bearing damages in an electrical drive train [3, 4]. A bearing damage causes characteristic frequencies in the structural vibration spectrum, which depend on the mechanical speed and the kind of bearing damage.
This contribution presents a diagnostic index for the damage detection based on this vibration. This index assesses the energy of the characteristic frequencies and is evaluated using the measured vibration data from a bearing without damage and a bearing with a damage in the outer race. Afterwards, the possibility of the failure detection by applying this index to the current signal is investigated and its capability evaluated. The proposed method does not base on the vibration transferred into the air-gap of the machine but the torque feedback of the bearing damage.

Test procedure

The test bench consists of a vector-controlled permanent magnet synchronous machine, a magnetic break (load), and a ball-bearing in a special test-bench housing. Figure 1 shows the schematic setup of the used test bench. The bearing housing is connected to the motor and the load only by shaft couplings. Thus, there is only minimal structural vibration transferred to the motor and the only relevant feedback of the bearing is the torque, transferred by the shaft. The currents are measured within the power source and are used for the machines control as well as for the bearing fault analysis. The bearing housing is equipped with accelerometers.

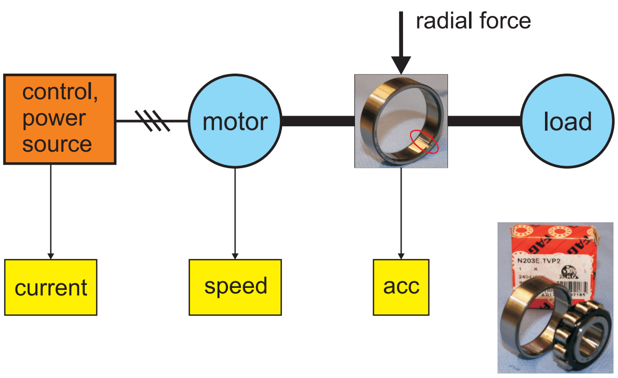

Figure 1: Schematic setup of the test bench.

For the experiment two bearings are used, a healthy one and a bearing with a damage on the outer race. The bearing housing has the possibility to adjust the radial force on the bearing up to 5 kN. The performed tests are startup operations with a steady acceleration up to nominal speed by variation of the radial force and the load. The used electrical machine is speed controlled. Its data are given in table 1.

type	permanent magnet synchronous
power	500 W
current	2.3 A
speed	3000 min^{-1}
torque	1.6 Nm

Table 1: Data of the used machine (rated values).

Fault index

The damage detection bases on an index, calculated from a spectral analysis of the vibration or the motor current. Only the expected harmonic orders (k) are used for the calculation (physically motivated). The fundamental order (k_0) of the bearing damage (outer ring) can be calculated in advance by geometric considerations [2]. For the bearing used in the experiment this order is 4.25. The expected signal frequencies for the vibrataion (f_{acc}) and the current (f_c) are given by:

$$\begin{aligned} f_{acc} &= k_{acc} \cdot f_{rotation} = n \cdot k_0 \cdot f_{rotation} \\ n &= 1, 2, 3, \ldots \\ f_c &= k_c \cdot f_{rotation} = f_{electric} \pm n \cdot k_0 \cdot f_{rotation} \\ n &= 1, 2, 3, \ldots \end{aligned} \tag{1}$$

The index can be calculated for each harmonic order by integration over the signal power (p) in an ordinal cut:

$$a = \int_k p(f, k) \mathrm{d} f_{rotation} \tag{2}$$

The precalculation of the fundamental fault order (k_0) bases on the geometric dimensions of the bearing. Since the production process causes tolerances, this order can vary around this value. An occurring slip also effects a decreasing order. Moreover, the spectral analysis is quantized, and therefore the explicit frequencies are not accessible. Thus, the calculation of the index not only uses the explicit frequencies but an area around the ordinal cut (e.g. $\pm 1\%$). Because of the quantization the integral function becomes a summation with a different number of summands for each order. Thus, the sum is

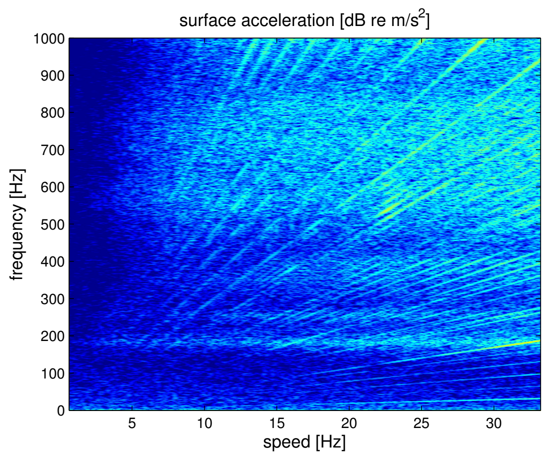

Figure 2: Healthy bearing - radial force 5 kN.

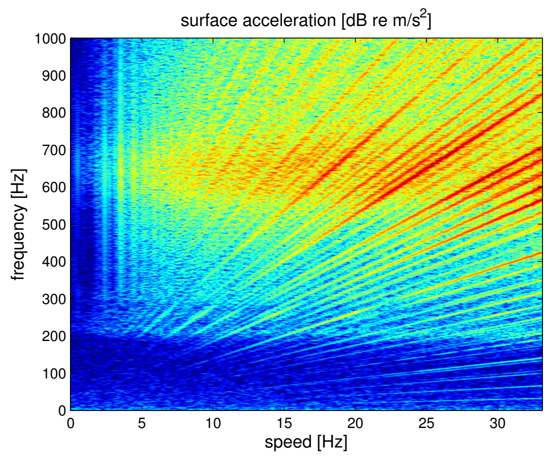

Figure 4: Faulty bearing - radial force 5 kN.

divided by this number to obtain a comparable signal power of the ordinal cut for each order.

$$idx = \frac{1}{z} \sum_{m=1..z} p(f, m) \quad (3)$$

Structural vibration

In this experiment a radial force of 5 kN is applied to the healthy bearing on the one hand and to the faulty bearing on the other hand. The vibration of the housing is measured and the fault index calculated from the spectrogram. The Figures 2 and 4 show the complete spectrograms for both experiments. The relevant parts ($f_{acc} \pm 1\%$ of (1) for the first ten fault orders) for the calculation of the index are shown in figure 3 and 5.

Applying the index calculation on this cut spectrograms by (3) one can obtain the index values for all investigated fault orders (shown in figure 6). For all orders the index signal of the faulty bearing is significantly higher than the index signal of the healthy one. This behavior is independent on the load and almost independent on the radial force. Only for very small forces near zero the fault index gives no reasonable results to differ the healthy and the faulty bearing.

Motor current

This experiment is equal to the one in the previous section but now the index is applied to the current signature of the electrical machine. The frequency orders are given by $f_c \pm 1\%$ of (1). Additionally to the multiples of the fundamental fault order the significant current frequencies have to be considered. It is not useful to take all integer current harmonics for the index calculation since the observed frequencies will cover the whole spectrogram. For example: the inclusion of the first 20 current harmonics (based on the shaft frequency) and setting n of (1) to 1 to 4, results in 160 different frequencies. With the range of $\pm 1\%$ the areas to observe within the spectrogram will overlap (figure 7). To overcome this, only significant current harmonics are considered. In this experiments this are 3,4,5,12,20 (based on the shaft frequency). The number of considered fault orders is thereby reduced to 40. Figure 8 shows the index for this 40 frequencies. The x-axis is related to k_0. Compared to the fault index of the vibration analysis the characteristic of the current fault index is not as distinctive. However, there are significant deviations for some orders that can be used for fault detection. Since the torque feedback is used for the algorithm, a load of the machine, with a corresponding increase of the current, could significantly influence the calculation of the fault index. This drawback can

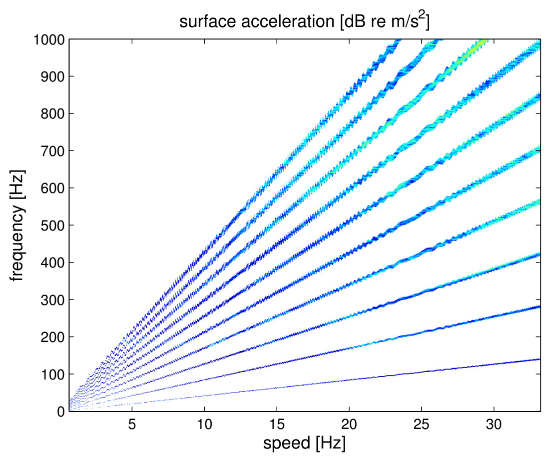

Figure 3: Healthy bearing - radial force 5 kN, index section.

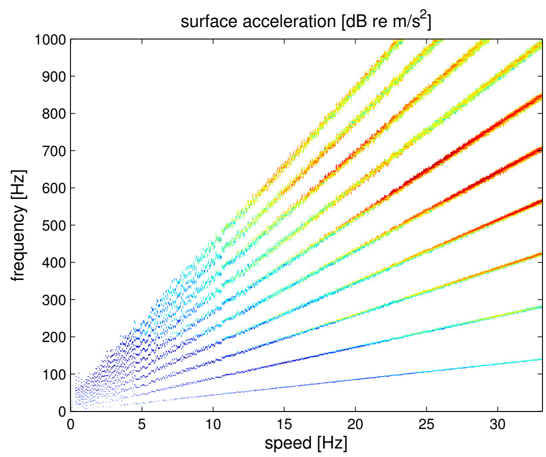

Figure 5: Faulty bearing - radial force 5 kN, index section.

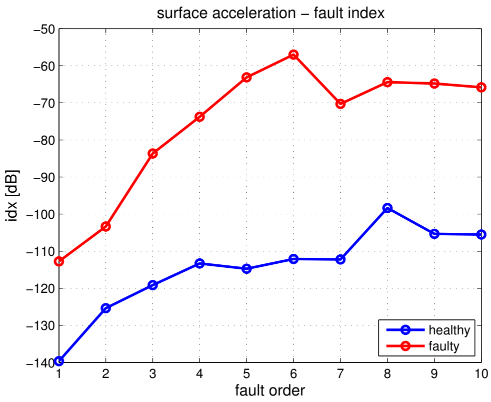

Figure 6: Vibration index signal of healthy and faulty bearing - 5 kN radial force.

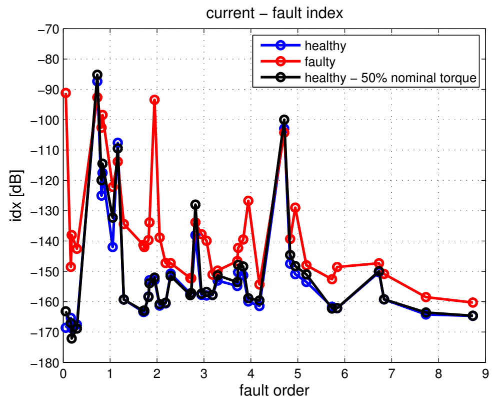

Figure 8: Current index signal of healthy and faulty bearing - 5 kN radial force.

be overcome by a meaningful choice of the considered frequencies. Some frequency orders should explicitly not be used for detection: e.g. the 4.7th order coincides with a natural harmonic of the machines current and does therefore mask the deviation caused by the bearing damage. A impression of the influence of a load is also included in figure 8. The black line represents the fault index for the healthy bearing but with a load of 50% nominal torque. Most of the fault orders are not affected. A more significant influence has the radial force on the bearing since it causes the torque feedback to the motor. A reduction from 5 kN to 2 kN makes a detection more difficult as can be seen in figure 9.

Summary and conclusion

A bearing damage within an electrical drive train is detected by analysis of the currents of an electrical machine. For this purpose the current time response is spectral analyzed. After that, a fault index is generated by calculation of a normalized signal power for specific ordinal cuts. These orders are determined in advance by geometric and physical considerations.
As a result, a bearing damage causes an observable signature in the index. But not all frequencies are suitable for the fault detection. Unfortunately, it is not possible to give a general rule for the choice of meaningful fault orders. They depend on the bearing, the damage, and the machine and have to be considered in advance before using the proposed index for bearing damage detection. Furthermore, the radial force given to the bearing in the experiments is quite high in relation to the machine size. However, the algorithm shows promising results. A further signal conditioning may enable a more reliable monitoring, that even small bearing damages and the damage progress can be detected, even at small radial forces.

References

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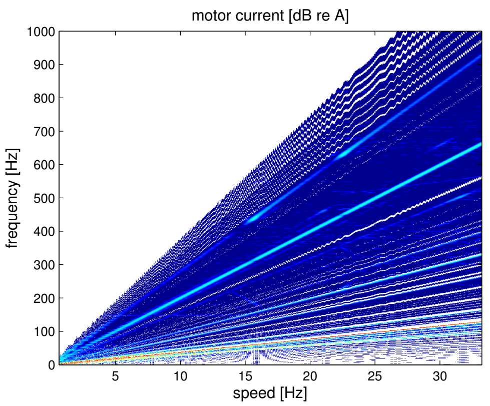

Figure 7: Overlap of the index sections.

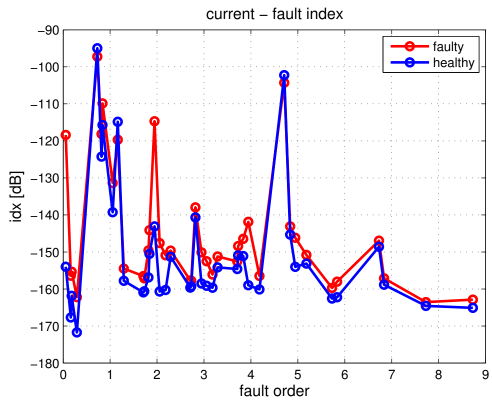

Figure 9: Current index signal of healthy and faulty bearing - 2 kN radial force.