Eddy current sensors for magnetic bearings of the textile spinning machines

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***Abstract*—The position sensors for magnetic bearings are very important parts of such a system. It is possible to say they are one of the most exacting part there because lot of conflicting demands are posed on them. This presentation describes the sensors for textile spinning machines which must have not only usual technical features but, in addition, they should fulfill the specific requirements of this industry, especially functionality in very dusty environment, resistance against foreign magnetic fields and last not least also potential for economical mass production without individual hardware setting and without selecting of specific components. Simply told, the prices at this market segment are forced down but the quality and reliability must be kept high.**

I. Introduction

A. Open End Spinning Process

One of the textile principles how to produce yarn is the open end spinning process, based on coiling of individual textile fibers in the spinning rotor with rotating speed often significantly over 100.000rpm. Conventional ball bearings for such speeds are expensive and they have limited lifetime. In addition, power consumption is high because of mechanical friction losses. Due to these facts, the alternatives were investigated and one of them was the magnetic bearing principle presented in [1]. Just at the beginning of the project, it was clear that a suitable position sensor will be one of the most significant components of such a system.

B. A History of Development

At first, a sample of the magnetic bearing without special sensors was tested, it had been assumed to sense the current of the bearing coils for a sensorless rotor position detection as proposed by [2]. This idea was left soon because of very low sensitivity and accuracy. As a next step, an eddy current sensor working on 500kHz with a synchronous rectifier has been investigated which provided good results but which was not suitable for mass production because individual hardware adjustment was needed and handling of the special thin wired coils was complicated. Also the influence of the magnetic field, generated by the motor driver, was visible because the working frequency of the sensor was not far off the used sensing frequency. We have also tested a capacitive principle which seemed to be very promising up to the point of high speed rotation when the noise on the floating electrode, which is the rotor, was too high, probably caused by static electricity. Optical methods were not investigated because of expected heavy dust deposit in the system. Because of these facts, we have concentrated on the eddy current sensor principle demonstrated in [3], trying to eliminate or to reduce all known disadvantages described above.

Figure 1. A sample of a HF transformer made of a PCB

C. A General Approach to the Problem

In the beginning there was a requirement to design a suitable sensor for a magnetic bearing within a relatively short time, using the known facts from the area of common general purpose electronics. It had been fulfilled by optimizing such methods under a lot of measurements and practical evaluations up to the moment when the results were good enough. No extremely high theories and no special expensive equipment was used but only step by step development on the right way to get a fit system for practical use.

II. Eddy Current Principle on a Higher Frequency

A. Sensor Design

From the principles that had already been investigated it seems that the eddy current principle could fulfill all the demands since it is enough reliable and accurate (see [4]). When a high frequency around 50MHz is used, then the sensing coils can be made as simple, cheap and easy to install PCB transformers when some general design rules as presented in e.g. [5] are followed. The design shown in Figure 1 will allow repeatable mass production with acceptable costs. In addition, the strong magnetic field with the frequency in the area of several kHz, which should be expected inside the system because of the motor drive signal, could be significantly suppressed, thanks to the very low inductance of the sensing coils. In this case, the coils had 5 windings what means about 200nH of inductance.

As an alternate way, ferrite coils with one winding were put up here but their features was not acceptable because certain of a non-linearity under the influence of strong magnetic field in the respective surroundings, see [6]. Therefore, only the

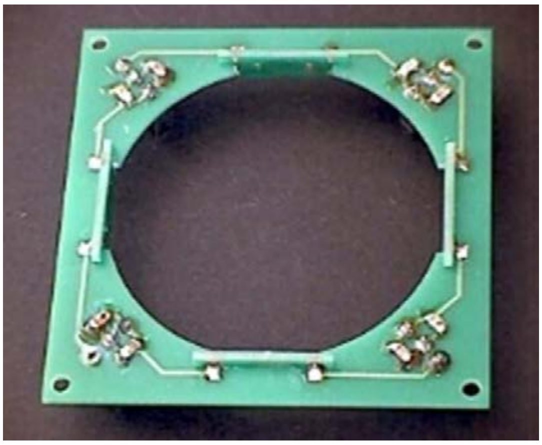

Figure 2. HF transformers in two orthogonal axes

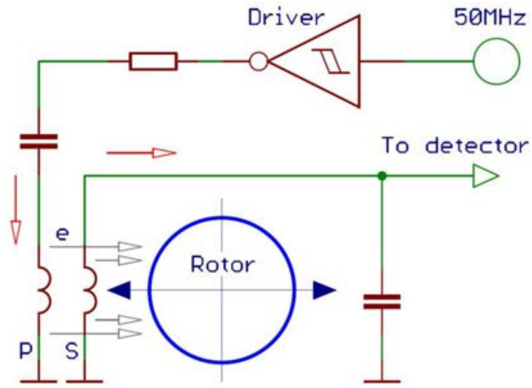

Figure 3. A principal single axis sensor configuration

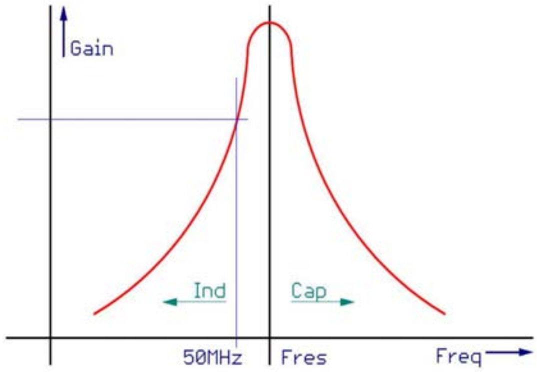

Figure 4. Sensor working point over frequency

air core PCB transformers were developed and used. These sensors were intended to be used for sensing a rotating part with diameter about 32mm, what means circumferential speed of approximately 250m/s at a rotor speed of 150.000rpm. This speed had no significant influence to the sensor features, no problematic behavior like for example missing target effect have been observed. The target part of the rotating element can be made of steel or aluminum alloy. The influence of these materials was measured as unessential. It is caused by skin depth which is given by

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \tag{1}$$

where ρ is the specific resistivity, ω stands for the angular frequency and where μ denotes the permeability (cf. [6]).

B. Signal Detection

Now, the only remaining problem which has to be solved is a precise detection of the output signal level without any ambient influences, especially temperature and manufacturing tolerances. Finally, the suitable solution was found in the technique known from radio engineering, see Figure 7 and Figure 8.

III. High Frequency Signal Detection

A. Signal Generation

There are always two single sensors in one axis of the rotor position detecting system. Figure 2 shows the actual sensor PCB.

The real position of the rotor is evaluated from the differential signal between them. These sensors are made as PCB transformers with their primary coils powered from one common source of HF signal. The induced voltage in the secondary coils reflects the rotor distance to this transformer because it is influenced by the eddy currents induced in the rotor's conductive surface, see Figure 3. To increase the basic sensitivity, the primary and secondary windings are designed as coupled parallel resonant circuits. Their resulting resonant frequency must be slightly higher than the frequency that the sensor is powered with, in order to keep the inductive character of those circuits as a monotonic function of the output signal, even if the rotor moves back and forth, see Figure 4.

As a rectifier, the depletion mode field effect transistor (FET) is used because it does not show a voltage drop as in diodes and because of its nonlinear transfer characteristic shown in Figure 5 and Figure 6with a certain range of temperature independence. After the detection of the HF signals in the operational amplifier circuit shown in Figure 7, there are two DC signals from both sensors in one axis available. These two signals are of the same value in case that the rotor is in the middle position. A difference between these two DC signals shows the deflection of the actual rotor position from the middle one. It means that such a signal could be used as an input for the stabilization of the rotor position in the active magnetic bearing system as described in [7].

B. Sensor Signal Evaluation Circuit

Such four sensors described above can be used directly inside the textile spinning unit in two orthogonal axes to sense the position of the spinning rotor. The output DC signals are evaluated using a differential amplifier for each axis, shown in Figure 9. The mechanical and electrical tolerances are then compensated by digital potentiometers with internal memory where the initial correction is stored after the assembly and initial calibration of each magnetic bearing. Together with the control electronics and with the power stabilization coils, this generates a compact system that was also documented in [7].

Table I
SKIN DEPTH VERSUS FREQUENCY RELATION

Material	Resistivity in $\frac{\Omega mm^2}{m}$	Relative permeability	Skin depth in mm						
			50Hz	500Hz	5kHz	50kHz	500kHz	5MHz	50MHz
Iron lamination	0.19	1000*	1	0.3	0.1	0.03	0.01	0.003	0.001
Aluminum	0.027	1	11.8	4	1.18	0.4	0.12	0.04	0.012
Copper	0.017	1	9.4	2.9	.94	0.29	0.09	0.029	0.009

* The actual relative permeability of iron strongly depends on the operation point in its B-H curve, this is an exemplary value.

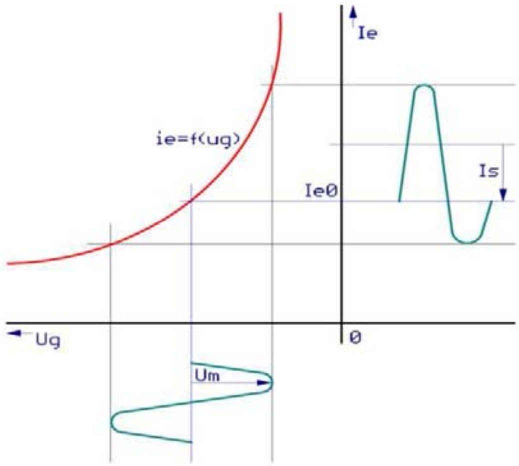

Figure 5. Typical transfer characteristic of depletion mode FET

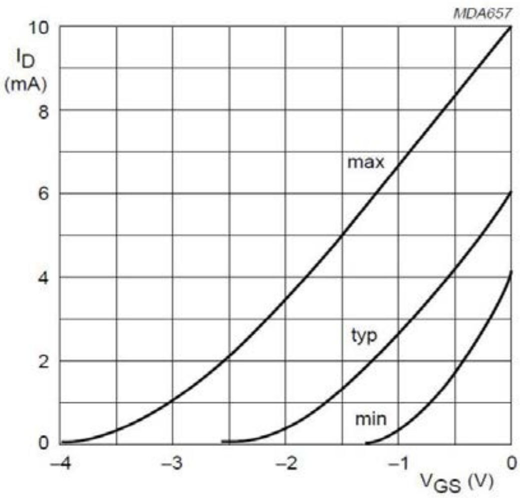

Figure 6. Real characteristic of depletion mode FET BFR31

IV. MEASURED PARAMETERS

The FET detector output is represented by the source voltage Ue which depends on the position of the rotor because of the eddy current effect. This voltage, of course, goes down when the rotor is leaving its center position and is approaching the secondary coil of the sensing transformer as shown in the right part of Figure 10. When the rotor shifts away from the transformer, the influence of the eddy currents decreases and the source voltage Ue goes to the upper limit value, see the left part of the Figure 10. Because of the above facts, the course

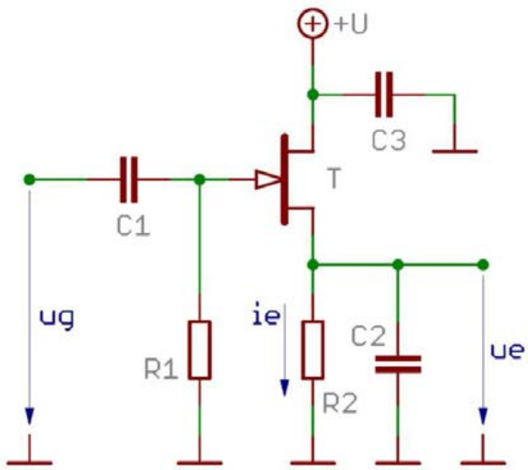

Figure 7. Sample of detector circuit

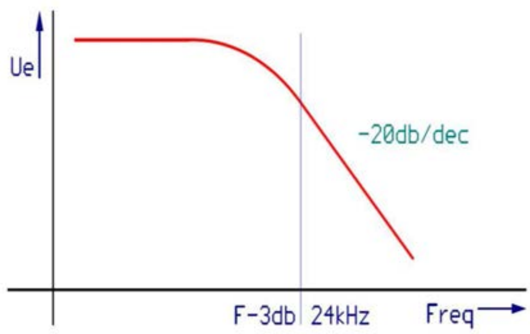

Figure 8. Frequency of characteristic low pass filter

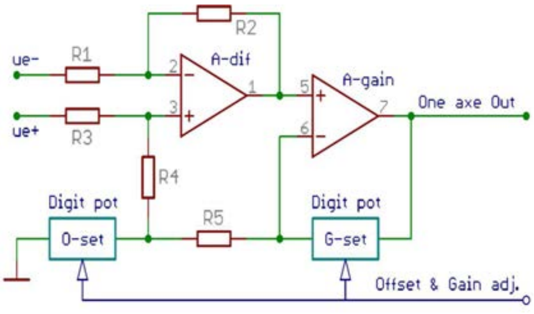

Figure 9. Principle of the differential amplifier for one axis with digital setting of the offset and gain

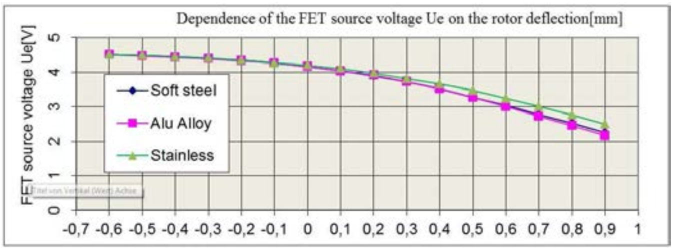

Figure 10. Relation between FET source voltage Ue and the rotor deflection from the center for various materials

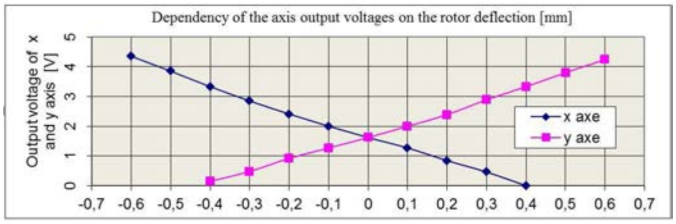

Figure 11. Resulting characteristics of the sensor system for both, x and y axes

of the dependency is not linear. What is interesting there, is that the curves are almost the same for rotors made of soft steel, special stainless submarine steel or aluminum alloy.

Using the differential amplifier of Figure 9 for subtracting the Ue voltages of the two FET detectors per axis results in an almost linear dependency between the rotor position and the differential output voltage. These curves are the same for both of x and y axes. The proportion of Ue as a function of the rotor shift, $U_e = f(shift)$, is approximately $1\frac{V}{mm}$ for one sensor around the middle position. After differential evaluation the final sensitivity is $2\frac{V}{mm}$. It is sufficient to use an amplifier with Gain of 2 to get the required ratio of $4\frac{V}{mm}$. The final response after those operations is displayed in Figure 11.

The resulting features of a complete one axis sensor are given Table II. These achieved parameters meet the required ones with a certain reserve. In accordance to Figure 9, the system allows to set the gain and to correct the tolerance offset independently and to store the correcting values into the internal memories of the digital potentiometers. It is remarkable that neither of components needs to be specifically selected or manually adjusted. One of the other big advantages is the fact that the correcting values are stored directly on the sensor board which allows to replace one sensor unit by another one without any necessary adjustment.

Table II
MEASURED VALUES FOR EDDY CURRENT SENSORS AS TWO-AXIS SYSTEM

Sensitivity in all range of the rotor position	$\frac{2V}{0.5mm}$
Normalized sensitivity	$4\frac{V}{mm}$
Output noise level on one axis output	$4mV_{pp}$
Theoretical accuracy	1μm
Practically usable accuracy	$10\mu m$
Measuring time for one position value	50μs
Number of measured values at 150.000rpm	8/rev

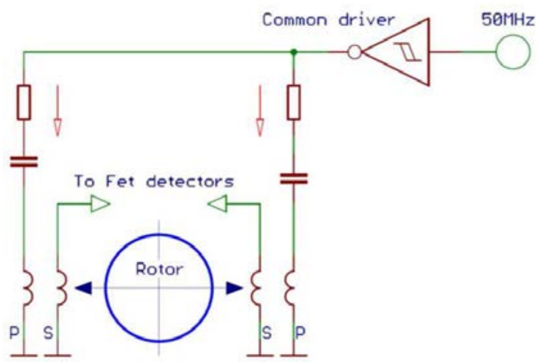

Figure 12. Principle of common power source for both primary coils of one axis

V. Temperature Stability

The next very important area of the sensor behavior in general is its temperature stability. There are lot of possibilities how the temperature could affect the sensors, since they are working on the eddy current principle. Practically, all the parts of the sensing evaluation chain have their certain temperature dependency. The most efficient tool for eliminating those effects is the differential principle of the signal handling from the AC source up to the final evaluation for each axis. Of course, the temperature stability of each individual part should be as high as possible. Keeping the principle above, the power source of the HF signal for the primary coils of the sensing transformers must be only one common for each axis as displayed in Figure 12. This is equally true for the DC powering of all differential circuits in one axis and for the referential voltages for the operational amplifiers.

The next important idea in this method is to use the same components with identical configuration for both sensors in one axis, believing that their temperature influences are also identical and they will be eliminated by the differential evaluation of the sensor signals. That should be right concerning all the passive and active components, an exception could be FET detector, only. To prevent such trouble, its working point must be adjusted to a temperature independent area by setting the optimal Id current, shown in Figure 13. The final temperature behavior of the sensing system which has been designed and made in accordance to the requirements above, is shown in Figure 14. In this experiment, the rotor was levitated magnetically and observed by the proposed sensor while the temperature was changed from 25°C at the start of the measurement to 60°C at the end of the 30 minute measuring duration. It is visible in this picture that the temperature influence on the differential output signal is below an absolute variation of +/- 10mV, representing a mechanical inaccuracy about $5\mu m$.

VI. Production and Operational Experience

The goal was to develop a position sensor for a magnetic bearing, suitable to be used in a textile spinning process and having specific functional features, such as accuracy of the position, reliability and resistance against the ambient influences which are especially temperature, dust and vibration. From

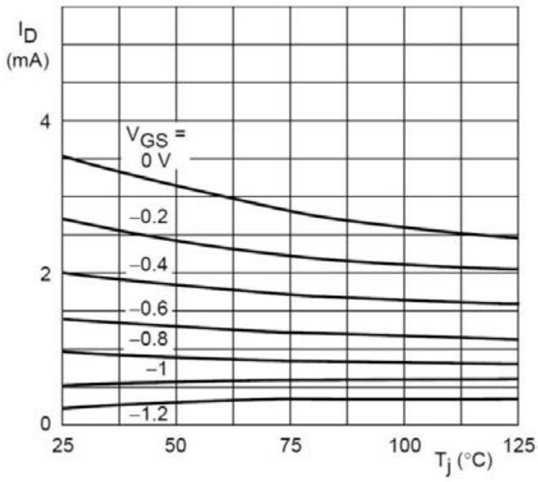

Figure 13. Real temperature behavior of depletion type FET

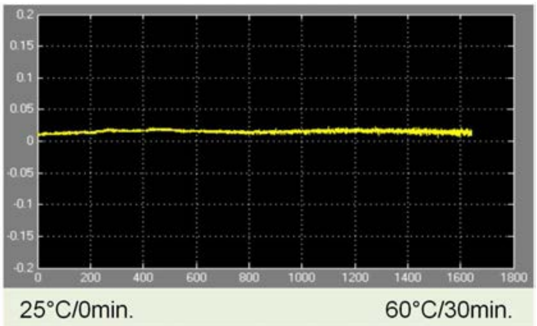

Figure 14. Measured temperature behavior of the one axis sensor system from 25°C to 60°C

the production point of view, there is no need for specially selected components and the individual adjustment is very easy and can be done automatically just via software as a last step of the final assembly. There are already some good practical experiences available, showing that there is a potential for some future industrial application of such a sensor concept. Two photos of the front and back side of the actual sensor board are visible in Figure 15. The complete schematic is given in Figure 16.

VII. Conclusion

This presentation describes the sensors of a high speed magnetic bearing for the textile industry which have been designed using known principles and keeping the known rules of such a design. A sensor unit was successfully designed and tested which is easy to produce at acceptable costs. Because of that, there is a good chance to use such a sensor also in other fields of magnetic bearing application with similar requirements.

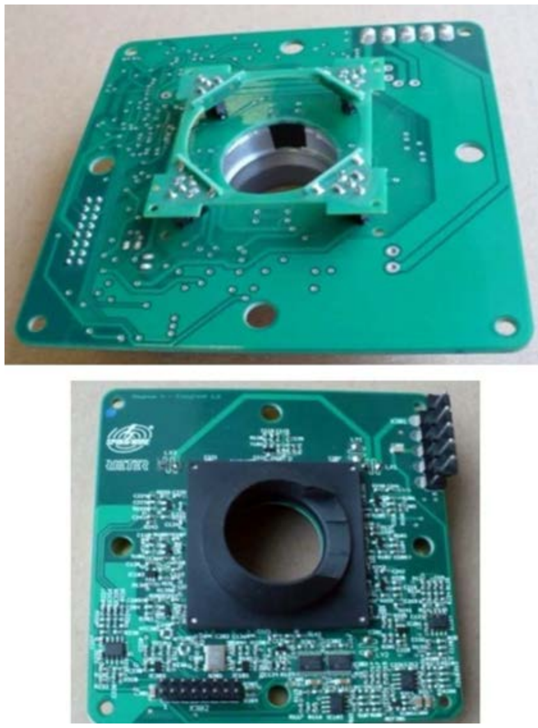

Figure 15. HF transformers in two orthogonal axes

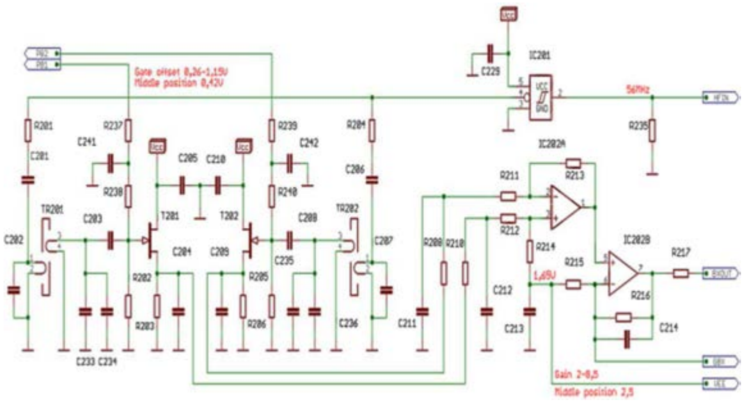

Figure 16. Complete sensor schematic

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