New Sensor Design for Rotor Displacement Measurement Based on the Coupled Oscillators Theory

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Abstract

Measurement of rotor position in bearingless motors and bearingless systems is of essence for proper operation. Insufficient resolution, sensor insensitivity and low sampling rate in measurement process leads unstable levitation and in worst case to the collision of rotor and stator which could end with motor destruction. Paper presents new concept for rotor position measurement based on Eddy current principle and Coupled oscillators theory in order to get accurate rotor position information. New concept is based on injection locking phenomena between coupled oscillators. Opposite pair of sensing oscillators are electrically coupled via resistor. In injection locking conditions phase shift between coupled oscillators is proportional to rotor movement. Phase shift was measured with Time to Digital Converter (TDC) and information is passed to Digital Signal Processor DSP over SPI communication link. DSP calculates the rotor position which is passed to power electronic circuit for rotor position control.

Introduction

Measurement of rotor position in bearingless motors and bearingless systems is common problem. Several sensor types are presented in literature for application in bearingless motors and for magnetic bearings systems. Most common type of sensors used in this type of applications is sensors based on Eddy current effect. Electronic circuit for this type of sensor is usually LC oscillating circuit. In case when rotor is closing to the sensing coil, the inductance is raising and leads to lowering down the oscillating frequency. Sensor position for rotor movement is presented on Figure 1. There are four sensors for rotor movement detection In this case rotor movement is proportional to the change of frequency. Problem with this type of measurement is that change of frequency is nonlinear because frequency of oscillating circuit is defined by equation 1.

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Problem of nonlinear relationship between rotor movement and change of frequency can be avoided if frequencies from opposite oscillators are subtracted. In that case rotor movement is in linear relationship with the frequency difference of opposite positioned sensors. (Figure 2)

Experimental result of rotor movement and change of frequency for full air gap is presented on Figure 2a. Blue and red surfaces on Figure 2b are frequency change of sensors caused by rotor movement. Green surface is frequency difference between sensors 1 and 2 from fig 1.

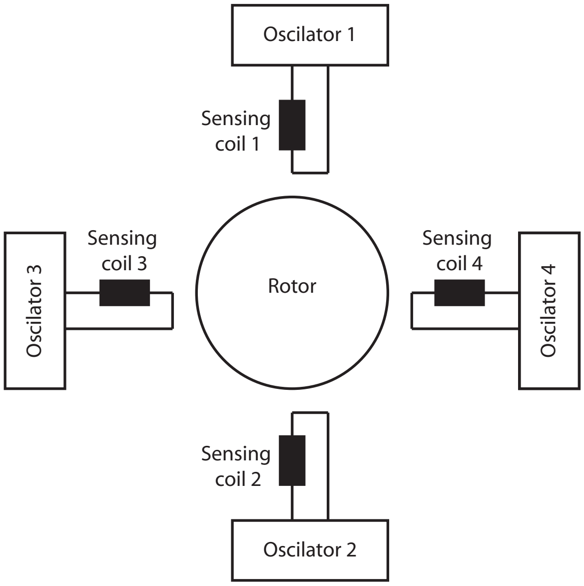
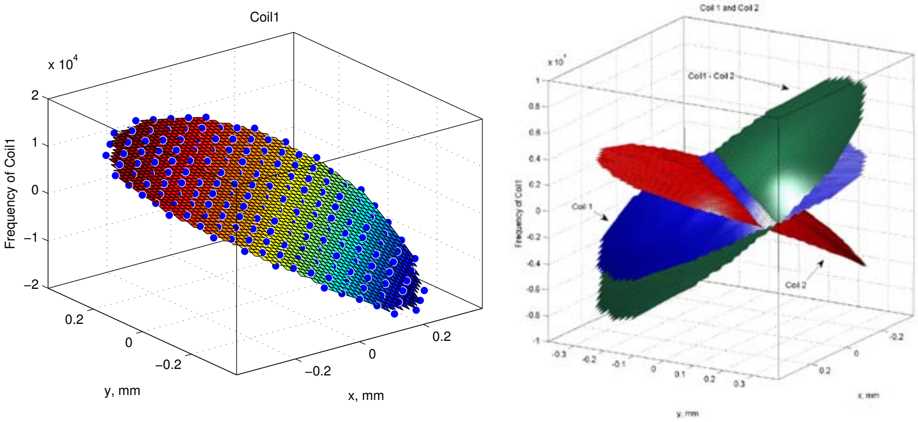


Figure 1. Sensor position for rotor movement measurement

Problem with this type of rotor position measurement is relatively small sensitivity and accuracy on sensor which is defendant on oscillator jitter.



a) b)

Figure 2. Change of frequency for rotor movement

a) Single coil b) Characteristic linearization

Only relatively close distance could be measured with this method with high accuracy (bigger frequency change), also higher sensitivity can be achieved only when rotor is relatively close to target.

1 Coupled Oscillators Principle

New approach in digital sensor design lies in injection locking principle between coupled oscillators. Two oscillators can be electrically coupled by resistor (Figure 3). If natural frequencies of oscillators are close enough and coupling is strong these two oscillators will be locked. When parameters of the oscillating circuit are changed, frequency of coupled oscillators will not be changed. Only change that can be noticeable is phase shift between oscillator output signals (Figure 4). This phenomenon is nonlinear phenomena and it is quite good described in the literature. (Adler, 1973) (Paciorek, 1965)Phase shift between oscillators is analytically expressed by Adler equation (1):

$$\frac{d\Delta\phi(t)}{dt} = \Delta f_0 - \frac{V_i}{V}\frac{f_0}{2Q}\sin(\Delta\phi(t)) \tag{1}$$

where φ is phase shift, f_0 is natural oscillating frequency.

When locking occurs phase shift becomes constant and expression (1) can be rewritten as in expression (2)

$$\frac{\Delta f_0}{f_0} = \frac{1}{2Q}\frac{V_i}{V}\sin(\Delta\phi(t)) \tag{2}$$

Locking range is derived from (2) and presented in expression (3).

$$f_L = \frac{f_0}{Q}\frac{V_i}{V} \tag{3}$$

In expression (3) f_L is frequency locking range. If natural frequency difference between two coupled oscillators in injection locking mode exceeds frequency locking range frequency slip will occur and oscillators will no longer be synchronized. In this case injection locking mechanism is broken. Equation (4) represents generalized Adler equation (1) and shows relationship of current I, phase shift θ and Q factor in the oscillating circuits (Prateek Bhansali, 2009).

$$\frac{d\theta}{dt} \cong \omega_0 + \frac{\omega_0}{2Q}\frac{I_{inj}\sin(\theta_{inj}-\theta)}{\frac{4}{\pi}I + I_{inj}\cos(\theta_{inj}-\theta)} \tag{4}$$

Under weak coupling conditions expression (4) can be further simplified (Razavi, 2004):

$$\frac{d\theta}{dt} \cong \omega_0 + \frac{\omega_0}{2Q}\frac{I_{inj}}{\frac{4}{\pi}I}\sin(\theta_{inj}-\theta) \tag{5}$$

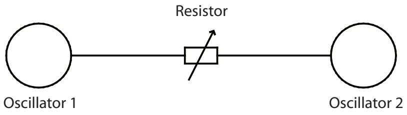


Figure 3. Coupling principle with resistor

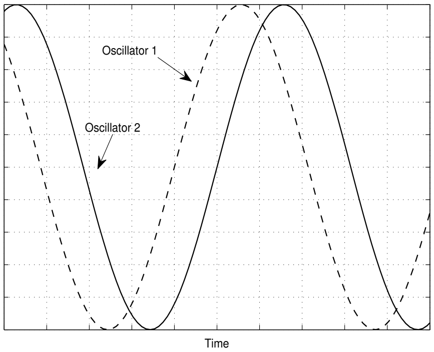


Figure 4. Phase shift in coupled oscillators

Proposed sensor electronic circuit for use in bearingless motor and bearingless systems application where target relative movement is necessary to monitor is presented on Figure 5. Basically sensor electronic circuit consists of sensing coil, two capacitors, resistor and hex inverter. Oscillator circuits used in this application is Collpits type oscillator (Gian Mario Maggio, 1999)Coupling of opposite pair of sensing circuits has been made by resistor connected between inputs of inverters. Coupling strength between oscillators can be changed by changing the values of the resistor (Ahmad Mirzaei, 2007) (Yayun Wan, 2005). For stronger coupling (lower values of resistance) sensitivity of opposite pair sensors will be decreased, so larger distances can be measured. Meaning of sensitivity in this type of application is: for the same rotor relative movement smaller phase shift will occur if sensitivity is smaller. For precision measurement and detection of smaller rotor movement, resistance of coupling resistor should be increased which leads to weaker coupling between oscillators. Problems in proposed method can occur if coupling between oscillators becomes insufficient; leading to the frequency slip and injection locking mechanism vanishing between coupled oscillators (Michael G. Rosenblum, 1997) (Yoko Uwate, 2007). Opposite pair Coupled oscillators output in dependence or rotor relative position is presented on the Figure 6. Case when rotor is closer to the sensing coil of oscillator 1 (and if oscillator 1 and 2 are electrically coupled) outputs of both oscillators are presented on the Figure 6.a. Existence of phase shift which is proportional to the rotor radial displacement can be noticed.

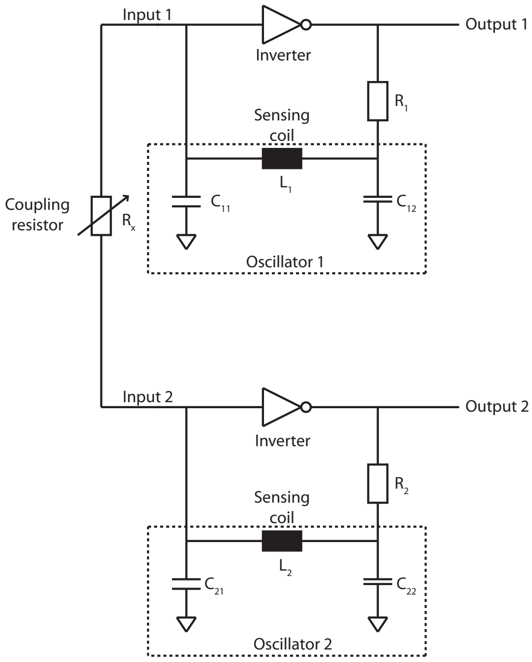


Figure 5. Proposed sensor electronic circuit for opposite pair of sensors

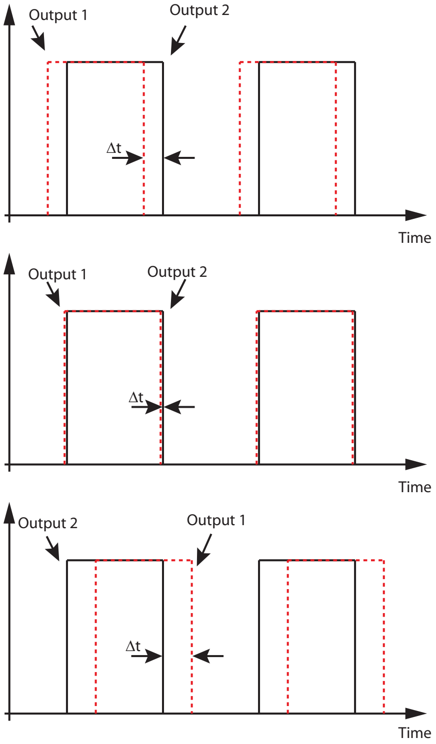


Figure 6. Oscillators output for different rotor positions

Figure 6.b represents central position of rotor when rotor is equally distant from both sensing coils. In this position some phase shift is expected because there are some inequalities between oscillating circuits (tolerances of used components) which are manifested in difference of natural frequency. In coupling case this will lead to the existence of small phase shift even if rotor is equally distanced from

sensor coils. On figure 6.c. rotor is moved closer to the sensing coil of oscillator 2 and phase shift between oscillators output is increased. On the Figure 6 lead lag between oscillator signals output can be noticed. On Figure 6.a oscillator 2 outputs is lagging by Oscillator 1 output signal, while on Figure 6.c there is opposite situation. (Neven Bulic, 2012)

2 Experimental sensor characteristic determination

For sensor experimental testing two layer printed circuit board (PCB) has been made with coupled oscillator's topology (Figure 7).

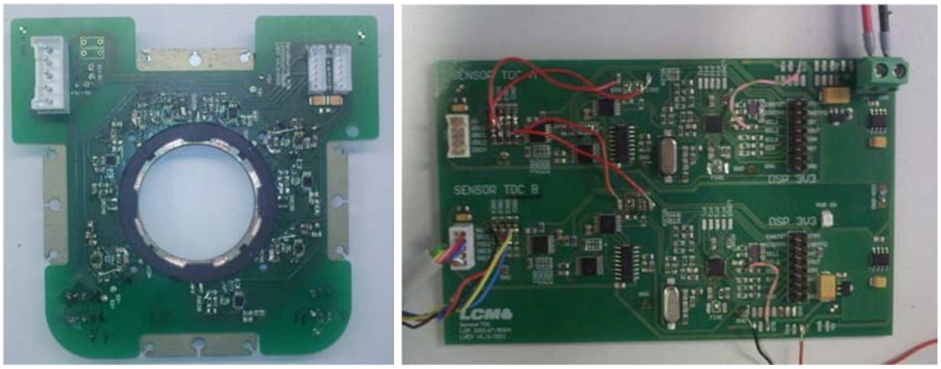


Figure 7. PCB board with sensor electronic and TDC board

Sensor PCB board has four oscillators each positioned by 90° geometrically. Opposite pairs of oscillators with sensing coils was electrically coupled by coupling resistor. PCB board with two TDC is shown on Figure 7.Pourpose of TDC board is to convert phase shift between oscillators into time as digital value. Each TDC on the TDC board is connected on outputs of coupled pair of oscillators. Block diagram of the system under test is presented on Figure 8. TDCs used in this application are ACAM TDC GP2 (ACAM). Signals from oscillating circuits are connected on the start-stop inputs of each TDC after signal conditioning. Signal from first coupled oscillator in coupled pair is connected on start input of TDC and signal from second coupled oscillator has been connected on stop input. Description of TDC can be found in literature (ACAM). TDC has been configured to work in measurement mode 2, with resolution of 22 ps and sampling rate of 40 kHz. Outputs of TDCs are connected via SPI communication link with TMS320F2808 DSP. TMS320F2808 has been selected to be used in this application regarding its communication capabilities (4 SPI communication channels) and calculation power (running on 100 MHz clock). Main purpose of DSP usage was to provide rotor position information in digital form for power electronic circuit which controls levitation of rotor and does digital filtering of measured signals based on the moving average principle. Histogram calculation for measured signals verification has also been implemented in DSP. Host PC is connected to the DSP via JTAG emulator connection.

Experimental setup for sensor characteristics determination and verification of proposed sensor method was consisted of: system under test, PC for data acquisition, test rig and oscilloscope. PC controls test rig which in small steps moves rotor across the air gap (in this application air gap is 0.2 mm). TDC used in this application measures time between falling edges of the coupled oscillators outputs. Time between falling edges of coupled oscillators output is equivalent to phase shift which was proportional to the rotor relative radial displacement. Overview of experimental setup is presented on Figure 9.

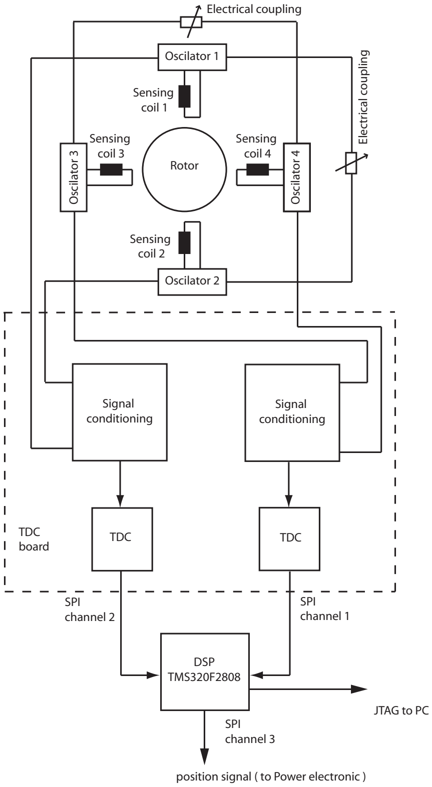


Figure 8. System under test block diagram

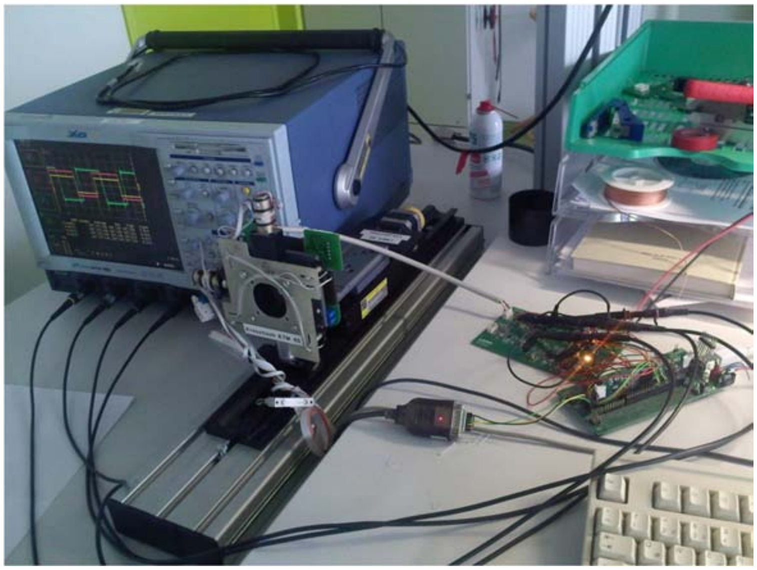


Figure 9. Experimental setup

Outputs of each oscillator are measured with four channel oscilloscope in order to ensure that oscillators were in locking region during whole measurement process. Measurement data were stored first in DSP RAM and then transferred via JTAG communication on host PC. Sensor output data were processed by Matlab software package. Sensor circuit characteristics presented on Figure 10 and 11 were determined with experiments conducted on test rig.

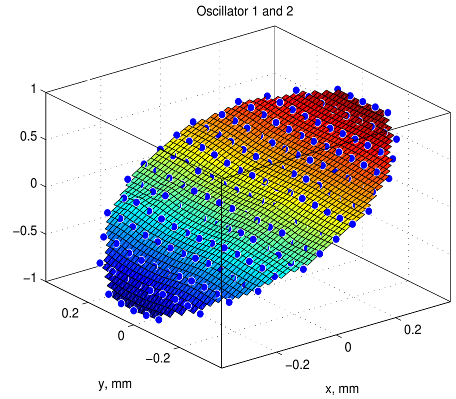


Figure 10. Sensor characteristic - osc 1-2 (3D-plot)

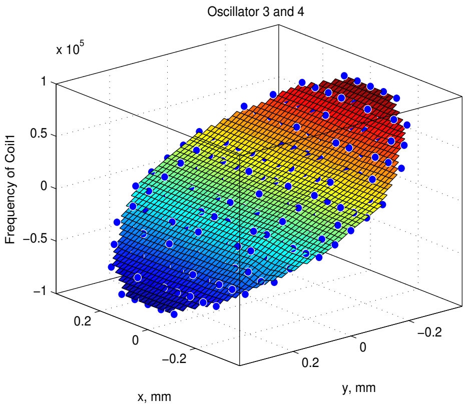


Figure 11. Sensor characteristic - osc 3-4 (3D-plot)

Phase shift is displayed in dependency of X and Y position of the rotor in air gap for each pair of coupled oscillators. Recorded characteristic was practically linear for whole region except small non linearity for rotor middle position in air gap. This nonlinearity is caused by a nonlinear injection locking mechanism which is explained in (Yoko Uwate, 2007). For practical application this nonlinearity can be taken into account and depending on operating region of sensor circuit can be neglected. Average value, maximum and minimum value for each measured point is presented on Figures 12 and 13 in 2D view. Smallest dissipation of min and max values occurs when coupling was strongest, which is obvious from observed from experimental results on the Figures 12 and 13 (rotor in center position). When locking becomes weaker difference between min and max values becomes higher. Such behavior can be explained with significantly smaller coupling forces between oscillators (Seiichiro Morot, 1994) and influence of noise on oscillating circuits. Also in case when rotor is not in center position natural frequency of each oscillator is different and oscillators are approaching to the edge of frequency locking window (Yoko Uwate, 2007) (Siegfried Silber, 2013)so oscillators become more likely to jitter.

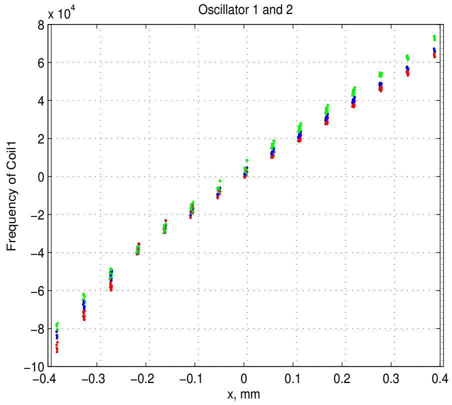


Figure 12. Sensor characteristics osc. 1-2 with Min, Max and AVG value)

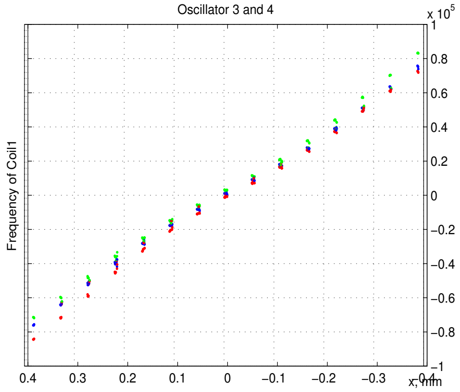


Figure 13. Sensor characteristics osc. 3-4 with Min, Max and AVG value)

Parallel with scope measurement, histogram for each measurement point is recorded with DSP and passed thru JTAG communication to the PC. Error histogram for each pair of oscillator (error distribution over x and y axes) is presented on Figures 14 and 15.

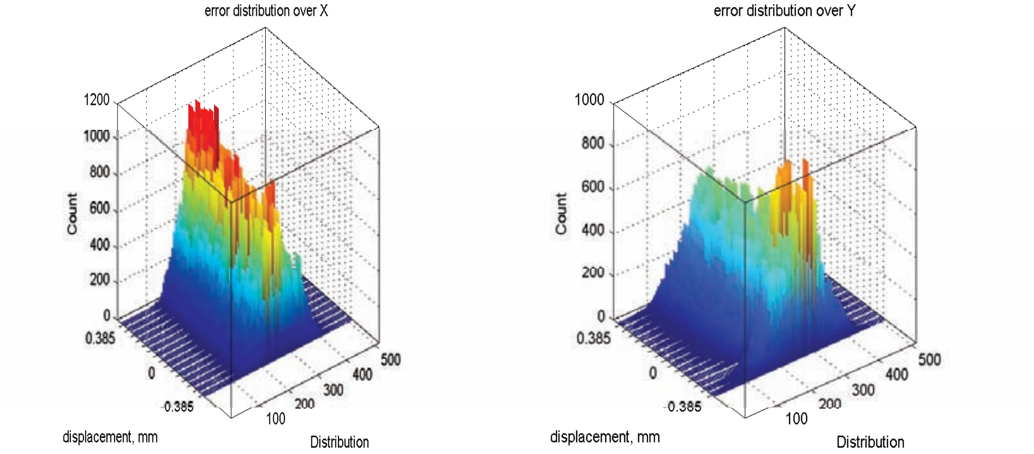


Figure 14. Oscillator 1-2 error distribution over x and y axes7

Measurements procedure has been done as follows:

- Automated test sequence from Matlab has been started.
- Test rig moves aluminum rotor in end position and in incremental steps rotor has been moved all over the air gap.
- Totally 700 points are recorded.

For each measurement point 512 measurements of current values of phase shift were measured. Based on this measurement average, minimal, maximal values and histogram were calculated in DSP and transferred to PC. Histograms show Gaussian distribution of noise in all axes for each pair of oscillating circuits.

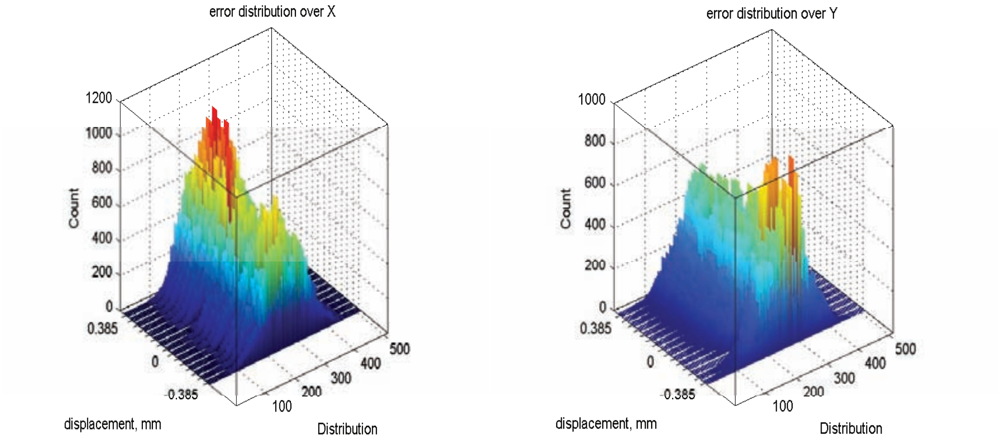


Figure 15. Oscillator 3-4 error distribution over x and y axes

3 Measurements conducted on magnetic bearing system

Developed PCB sensor electronic board was mounted in the magnetic bearing system. Experimental setup is presented on the Figure 18.

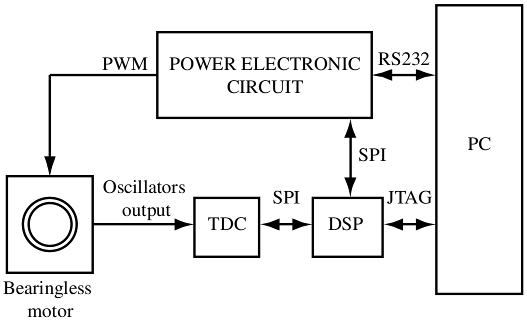


Figure 16. Experimental setup

DSP has been sending rotor radial position over SPI communication to the power electronic circuit. Description of the motor under test can be found in (Siegfried Silber, 2013). Power electronic circuit for magnetic bearing system control was parameterized via the Matlab over RS232 communication with PC. Experimental results were recorded in Matlab and they were extracted from DSP via JTAG communication with PC. On Figure 17. sensor signals of rotor position are presented without influence of PWM from power electronic circuit. In this case rotor is not levitating and has been positioned in geometrical centre of air gap.

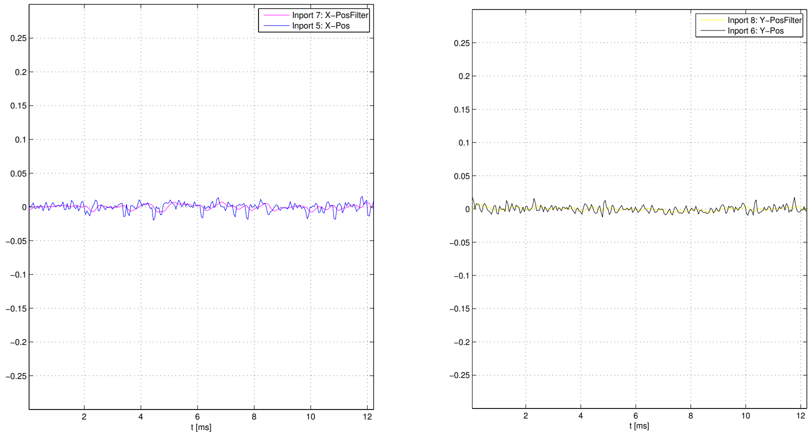


Figure 17. Sensor signals with no PWM

Sensor signal for rotor position in levitation is presented on the Figure 18. Position signals are filtered with the low pass filter with cut off frequency of 2 kHz. Ordinate position from -1 to 1 represents rotor position in air gap in p.u. Under the influence of PWM signal from magnetic bearings sensor signal is corrupted with the noise. For levitation purpose filtering with 2kHz (low pass filter) was sufficient to remove influence of PWM on stabile levitation.

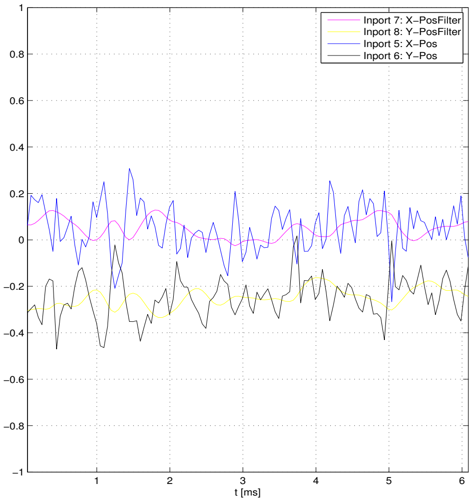


Figure 18. Sensor signals - levitation

4 Conclusions

Researches presented in the article were related to application of coupled oscillators in injection locking mode on rotor position measurement. Measurement principle was based on Eddy current effect and fact that change sensing coil inductance of leads to the change of oscillating circuit frequency. In case when coupled oscillators frequency was in frequency locking window, changes in sensing coil inductances leads to phase shift between coupled oscillators. In frequency slip case between oscillators there was possibility to measure rotor position based on phase shift so frequency locking window must be taken into account. Experimental results show that sensor characteristic was near linear for whole operating region. In rotor central position experimental results shows smallest deviation of signal. Experimental data shows that noise has greater impact on sensor signal quality when rotor approaches to the edge of air gap. Histograms over x and y axes shows normal Gaussian distribution which was equally distributed over axes with higher values of error on the edges of air gap. Levitation experiment shows that proposed sensor principle can be used in magnetic bearing system and bearingless motors for rotor or shaft position measurement. From experimental results influence of PWM to the sensor signal can be observed. For rotor position measurement this impact can be removed with low pass filter with cut off frequency of approximately 2kHz. Further work will be focused on improvement of sensor electronic circuit and in PWM influence reduction on sensor signal quality.

5 Acknowledgment

The research leading to these results has received funding from the European Union Seventh Framework Program (FP7/2007-2013) under grant agreement number 251396.7 The used DSP software toolbox M2C for control design was developed within the Austrian Center of Competence in

Mechatronics (ACCM) GmbH, a K2-centre of the COMET program of the Austrian Government. The authors thank all partners for their support.

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