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IMPLEMENTATION OF METHODS OF STATE DIAGNOSIS IN AN EXISTING SOFTWARE APPLICATION FOR ACTIVE MAGNETIC BEARINGS

MASTER THESIS

Zittau 2015 **Bc. Radek Pujman**

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Implementation of methods of state diagnosis in an existing software application for active magnetic bearings

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Implementace metod diagnostiky stavu v existující softwarové aplikaci pro aktivní magnetické ložiska

Diplomová práce

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Tasks:

1. Familiarization with the program "maglap++" written in C++ and the dissertation "Neuartige Verfahren für die Überwachung und Diagnose von aktiv magnetgelagerten rotierenden Maschinen"
2. Formulation of the algorithms and integration in the existing program structure
3. Design and realisation of a suitable graphical user interface as an Android app
4. Test of the client-server-system
5. Documentation of the results.

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Abstract

The aim of this thesis is to develop software for monitoring of active magnetic bearings. Known diagnostic methods from dissertation work “Neuartige Verfahren für die Überwachung und Diagnose von aktiv magnetgelagerten rotierenden Maschinen” are implemented in the diagnostic program and optimized for monitoring of MFLP device. The diagnostics methods are divided to methods that use limit flags and methods that use fuzzy logic. Limit monitoring is essential for state evaluation and it is also used for detection of critical values in measured signals. Fuzzy logic monitoring is used for diagnostics of active magnetic bearings control loop. Program verification is done with real measured data from MFLP in addition to simulated signals.

Key words: Active magnetic bearing, state diagnostics, signal processing, error and warning recognition

Abstrakt

Cílem této práce je vývoj software pro monitoraci aktivních magnetických ložisek. Známé metody diagnostiky z dizertační práce “Neuartige Verfahren für die Überwachung und Diagnose von aktiv magnetgelagerten rotierenden Maschinen” jsou implementovány v diagnostickém programu a optimalizovány pro monitoraci MFLP zařízení. Diagnostické metody jsou rozděleny na metody, které používají limitní vlajky a metody, které používají fuzzy logiku. Limitní monitorace je stěžejní pro vyhodnocení stavu a je také použita k detekci kritických hodnot v měřených signálech. Monitorace využívající fuzzy logiku je určena pro diagnostiku řídící smyčky aktivních magnetických ložisek. Verifikace programu je provedena s reálnými daty změřenými na MFLP doplněných o simulované signály.

Klíčová slova: Aktivní magnetické ložiska, diagnostika stavu, zpracování signálu, rozpoznání chyb a varováni

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List of abbreviations, symbols and indexes

Abbreviations

A/D – analog to digital

AC – alternating component

AMB – active magnetic bearing

CCD – charge-coupled Device

D/A – digital to analog

DaMa – class data managing

Diag – structure of diagnostics

DMM – data managing module

DSP – digital signal processor

e.g. – for example

etc. – and other things

FLMM – fuzzy logic monitoring module

GUI – graphical user interface

HT AMB – high temperature active magnetic bearing

ID – identity

IDE – integrated development environment

LF – limit flag

LiMo – class limit monitoring

LMM - limit monitoring module

MeVal – measured values structure

MFLP - Magnet- und Fanglagerprüfstand

N/A – Not available

PMB – passive magnetic bearing

PWM - pulse width modulation

SEM – state evaluation module

StEv – class state evaluation

VPM – variable preparation module

Symbols

μ - magnetic permeability

μ_0 – free space permeability

μ_r – relative permeability

a – coefficient in linear function

A – effective value of position to effective value of control current ratio

A_a – cross-sectional area

B – big

b – coefficient in linear function

B – magnetic flux

d – Boolean value from diagnostic vector

ds – differential length

f – force

f_s – sampling rate

H – magnetic field

i – current

i_0 – bias current

i_c – control current

i_c –control current

K_1 – coil constant

l – length of group of limit flags

L_{bc} – inductance of bearing coil

l_{fe} – length of magnetic circuit

n – general number

N – normal

n_s – number of samples

r – distance from wire

R – effective value of position to effective value of control signal ratio

R – rotor diameter

s – air gap

S – small

S – switch (transistor)

s_0 – nominal air gap

t – time

u – voltage

u_{bc} – voltage on bearing coil

u_{DC} –supply voltage

u_i – voltage input signal

u_{ic} – voltage from current sensor

u_{tr} – voltage on transistor

V_1 – permeability and coil design dependent variable

V_2 – permeability and coil design dependent variable

W – effective value of control current to effective value of position ratio

x – displacement

x – general signal

x – x axis

x – x coordinate

x_A – distance from sensor A

x_B – distance from sensor B

x_{sens} – measured displacement

y – y axis

y – y coordinate

z – z axis

ΔR – rotor growth

Indexes

- – negative

+ – positive

x – in x axis

y – in y axis

z – in z axis

1. Introduction

A magnetic bearing is a device constructed for supporting a load by magnetic levitation. This technical solution solves many problems like lubrication, friction and wear of bearings. Due to contact-free support of a load, very high speed of rotation can be realized. Without lubricant magnetic bearings can be used in clean room environments. Maintenance also decreased due to absence of surface wear. On the other hand, there are some disadvantages of magnetic bearings that come from complexity of these devices. Large number of components causes initial costs much higher compared to classical bearings. However, return of the investment can be short due to much higher efficiency of the system. [9, 16]

A basic classification of magnetic bearing is made into active and passive bearings. Passive magnetic bearings (PMB) use for hovering a load permanent magnets only. This type of bearings are not electrically powered and cannot be controlled. Active magnetic bearing (AMB) needs to be electrically powered and are actively controlled by a controller. This work is mainly focused on the active magnetic bearings, because AMBs are the most used types. [9]

As mentioned above, purely **passive magnetic bearings** creates bearing forces by permanent magnets only. This type of magnetic bearing does not need any electric supply but cannot be controlled. Passive magnetic bearings have constant properties given by its mechanical construction. These constant properties includes very low damping, that can be added by another source of damping, e.g. by a fluid around a levitated body. The construction of PMB also does not allow (it is physically impossible) to control rigid body in all of its six degrees of freedom and there is every time at least one unstable degree of freedom. However, combination of AMB and PMB (hybrid AMB/PMB system) can lead to reduction of system complexity and cost. [13]

PMBs provide better performance than AMBs for example in blood pumps or artificial hearts. In this case, damping is improved by blood that surrounds the rotor. Also there is necessary to have large bearing forces due to large air gaps.

In **active magnetic bearing** are bearing forces actively controlled. Most used principle of magnetic bearing is creating contact free magnetic field forces by actively controlled electromagnet. For operating of the AMB is required following equipment: displacement sensors, electromagnets, controller, power amplifiers and current source. Signals from displacement sensors are processed by a control system that sends commands to the amplifiers. The amplifiers cause the current flow through electromagnets to generate bearing forces on given rotor. For complete controlling of shaft position there must be at least two radial bearings and one axial bearing. [9, 16]

2. Hardware components of AMB

As mentioned in last chapter, there is necessary hardware equipment for construction of AMB. Minimum equipment for AMB system with two radial and one axial bearing contains ten electromagnets, at least five displacement sensors, one evaluation unit, one control unit (with A/D and D/A converters), five power amplifiers and one constant current source. Additionally each active magnetic bearing has back-up bearing that support the shaft in case of shutting down of AMB system or in case of power failure. [2, 9]

2.1. Electromagnets

The electromagnets are used for attracting ferromagnetic rotor by generating forces that are caused by currents in the coils. For understanding of principles how electromagnet works it is necessary to briefly review magnetism.

Every magnet has two poles – north and south. Between these two poles exist a magnetic field with lines that create closed loop from north to south pole. This magnetic lines are also created by current that flows through a coiled wire. The magnetic field can be described by following equation 2.1 and current trough a single loop of wire leads to equation 2.2. [9, 12, 16]

$$\oint H ds = i \tag{2.1}$$

$$H = \frac{i}{2\pi r} \tag{2.2}$$

H is the magnetic field, *ds* is the differential length of wire, *i* is current and *r* is distance from wire. For *n* loops of wire is result from equation 2.2 multiplied *n* times. Calculation of magnetic flux density can be done by equation 2.3. [9]

$$\vec{B} = \mu \vec{H} \tag{2.3}$$

Where magnetic permeability μ can be described by equation 2.4.

$$\mu = \mu_0 \mu_r \tag{2.4}$$

Constant μ_0 is permeability of free space and constant μ_r is relative permeability of the used material.

Materials with magnetic permeability much higher than one are called ferromagnetic. The feature of ferromagnetic material is increasing the magnetic flux density when it is inserted to magnetic field as already showed in equation 2.3. In case of decreasing of magnetic field, the magnetic flux density goes down by different path creating a hysteresis. [4, 9, 16]

2.1.1. Generated forces

Lorentz force is an force that act on electric charge (or conductor in electromagnetic field) that moves within magnetic field. After simplification can be described as [9]

$$\vec{f} = \vec{\imath} \times \vec{B} \tag{2.5}$$

Reluctance force is generated on the boundary of different magnetic permeabilities in presence of magnetic field. Direction of the generated force is perpendicular to the interface of the two surfaces. Considering the typical shape of the rotor, the reluctance force can be expressed as following

$$f = \mu_0 \left(\frac{ni}{l_{fe}/\mu_r + 2s} \right)^2 A_a \cos\alpha \tag{2.6}$$

where i is current, s is air gap, l_{fe} is length of magnetic circuit, n is number of coils, A_a is cross-sectional area perpendicular to l_{fe} and α is angle of force affecting the rotor. [9, 16]

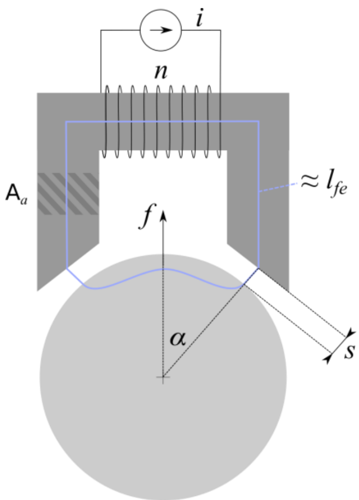


Figure 1 – Single electromagnet acting on shaft

The force from magnet does not increase linearly with displacement like in case of spring. In case of magnet (or electromagnet) is the force inversely proportional to the square of an increased distance. Also when the distance between electromagnet and levitated object decreases, the acting force stabilizes when the material of levitated object is saturated with the magnetic flux. For successful controlling of position of the levitated object, *magnetic force must be linearized* around the working point. Linearization is done by applying the constant bias filed that can be created by constant bias current i_0 in electromagnets or by adding a permanent magnets into the AMB. [4, 9, 16]

2.1.2. Arrangement of electromagnets in AMB

For every axis there are two electromagnets in opposite direction, e.g. upper and lower coil. These electromagnets are very often used for differential operation – controlling opposite electromagnets as a pair. It means that control current i_c is added to one coil and subtracted from the current of the opposite coil. This leads to increase of the bearing force of one electromagnet and decrease of the force from opposite electromagnet. On the following picture is shown differential operation with opposite electromagnets. In this case, the bias field is created by bias current i_0 that flows in same coils as i_c. ([4, 9]

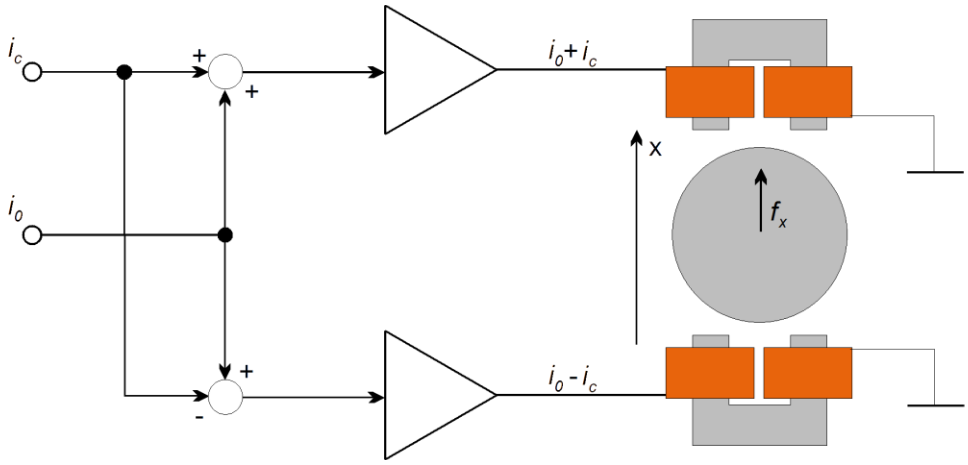


Figure 2 – Differential operation of the electromagnets

The force f_x can be calculated by following equation.

$$f_x = f_+ + f_- = k\left(\frac{(i_0+i_c)^2}{(s_0-x)^2} - \frac{(i_0-i_c)^2}{(s_0+x)^2}\right)\cos\alpha \tag{2.7}$$

Where s_0 is nominal air gap and k is defined as

$$k = \frac{1}{4}\mu_0 n^2 A_a \tag{2.8}$$

After linearization that is necessary for the controller, f_x can be described as

$$f_x = \left(\frac{4ki_0}{s_0^2}\cos\alpha\right) i_x + \left(\frac{4ki_0^2}{s_0^3}\cos\alpha\right) x \tag{2.9}$$

[9]

2.2. Sensors

In AMB system is possible to find few types of sensors. Displacement sensors are used for contactless measuring position of the levitated rotor. In addition speeds, currents, flux densities and temperatures can be measured. [16]

2.2.1. Types of displacement sensors

The position sensors must be able to measure the distance without contact and moreover the measured surface is rotating. Sensors must fulfil measuring range, linearity, sensitivity, resolution and frequency range requirements. Rotation of the object with bad surface or with bad geometry results to noise disturbances in the position measurement. Furthermore there must taken into account temperature changes, noise immunity (e.g. noise from alternating fields of electromagnets), environmental factors (e.g. dust or vacuum), mechanical factors (e.g. vibrations) and electrical factors (e.g. grounding issues). There are several types of displacement sensors, that can be used. These types are briefly discussed bellow. [16]

Inductive displacement sensors works on principle of inductance. A coil with ferromagnetic core is driven by an oscillator with frequencies approximately from 5 kHz up to 10 kHz. An electronic system board is measuring inductance and convert changes of inductance to output voltage, that is proportional to displacement. The inductance of the coil is changed when ferromagnetic material (e.g. levitated shaft) change its position to the sensor. Commonly, two inductive sensors are opposing each other and are operated differentially in a Wheatstone bridge circuit with constant frequency AC signal. This arrangement produces nearly linear signal. Inductive displacement sensors are not sensitive to external magnetic fields produced by bearing electromagnets, but big disturbances can occur when bearing electromagnets are driven by switched power amplifiers with frequency similar to modulation frequency. [10, 16]

Eddy current sensors works on principle of induction of eddy currents in conductive object near the sensor by alternating magnetic field. The strength of the Eddy currents decrease with the distance of the excitation electromagnetic coil. The electromagnetic coil is driven by high frequency alternating current (in range of 1 MHz up to 2 MHz) and Eddy currents are induced in the conductive object, thus it is absorbed energy from excitation coil. Disturbances in the signal can be caused by inhomogeneities in rotating object. The sensors also must be shielded because of application near to the bearing magnets. Sensors can influence each other, so there must be minimal distance between sensors. Main advantages of Eddy current sensors are resistance to dirt and relatively low price. [3, 5, 16]

Capacitive displacement sensors uses the effect of changing capacity of plate capacitors due to changing of distance between capacitor's electrode and the object. Constant frequency about 50 kHz signal runs through the sensor and the voltage amplitude is dependent on the distance between sensor's electrode and the measured object. The capacitive displacement sensors are interesting for their very good resolution (hundredth of micrometer), but are expensive. The noise in output signal can be caused by electrostatic charging of contactless rotor. Capacitive displacement sensors are also sensitive to dirt that changes dielectric constant in the air gap. [1, 16]

Magnetic displacement sensors measures the size of the air gap by measuring of flux density *B.* There is electromagnet that is driven by constant current and Hall sensor that measures flux density. The magnetic displacement sensors are sensitive to external magnetic fields that are created by bearing coils. [16]

One possible principle of **optical displacement sensors** is a covering of light source by a levitated object and measuring the light intensity by light-sensitive sensor on the opposite side. The levitated object works as a light barrier. Second principle is similar to the first but the light is reflected by the object. The light intensity on the sensor also give us information about shaft position. The third possible principle is application of image sensor (e.g. CCD sensor). Light and dark pixels can be counted in the created image, thus position can be determined. The optical displacement sensors are very sensitive to dirt and the resolution is limited by diffraction effects. [16]

2.2.2. Arrangement of displacement sensors in AMB

A commonly used arrangement are two installed Eddy current displacement sensors for each axis in AMB. These two sensors are operated in differential mode so disturbances that act on both sensors in the same way (e.g. temperature drift, rotor growth) are compensated. On the following picture is shown differential operation of the displacement sensors. [4]

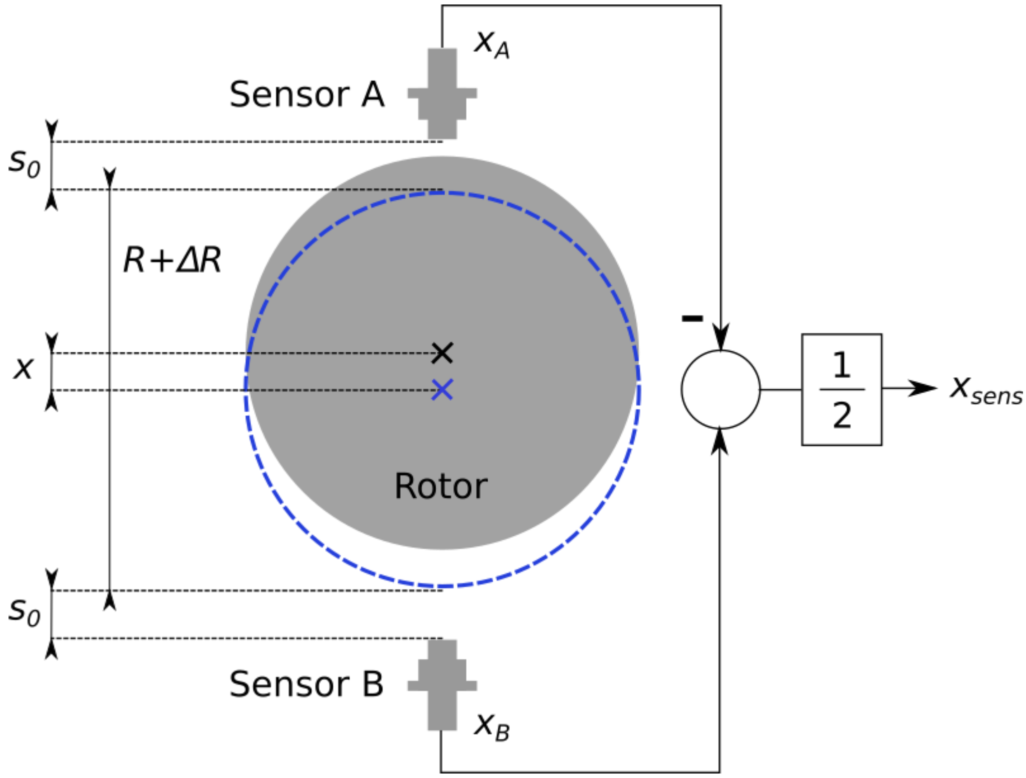


Figure 3 – Differential operation of the sensors

Measured position is calculated by following equations:

$$x_{sens} = \frac{x_B - x_A}{2} = x \tag{2.8}$$

$$x_A = s_0 - x - \Delta R \tag{2.9}$$

$$x_B = s_0 + x - \Delta R \tag{2.10}$$

Where s_0 is nominal air gap, x_A and x_B are measured distances from sensor A and B, x is real displacement and ΔR is rotor growth.

2.2.3. Current sensors

Current measurement is usually done by use of Hall sensor that detects magnetic field. Hall effect describes difference of voltage on an conductor that is inserted into perpendicular magnetic field. Deflection of the current i that floats through the conductor is proportional on the magnetic flux density B. This deflection leads to different electrical potential on longitudinal sides of the conductor - Hall voltage.

In case of current measurement, the Hall sensor is situated in magnetic loop excited by one or several turns of current *i* that is measured. A controller is balancing measured flux density by auxiliary coil and power amplifier. Input signal u_i of the power amplifier is also the measured value of current *i*. [8, 14, 16]

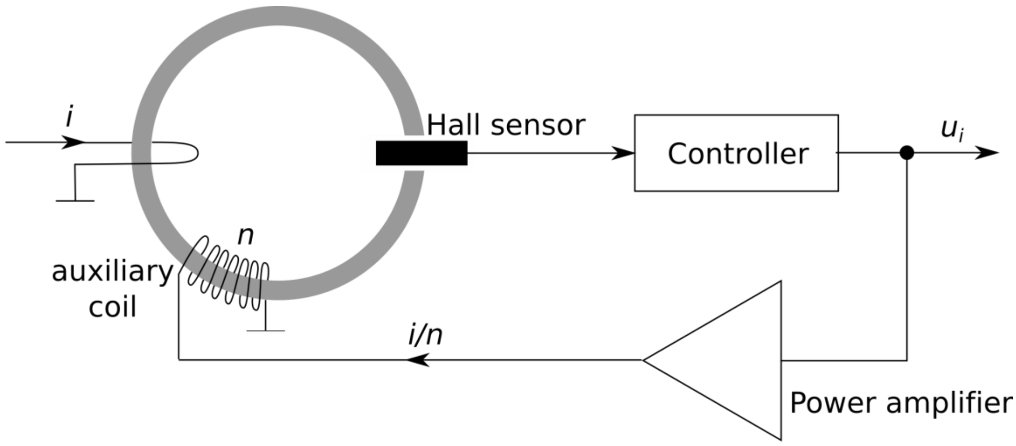


Figure 4 – Current measurement by Hall sensor

2.3. Power amplifiers

The function of the power amplifiers is to convert control signal from controller to control current that is driven into bearing electromagnets. There are two types of power amplifiers – analog and switching amplifiers.

2.3.1. Analog power amplifiers

The analog amplifiers (linear amplifiers) have simple structure with transistor as a central element. Analog amplifiers are used for applications that require low power (below approximately 0,6 kVA). Advantage of analog power amplifier is smoothed current output. However, there is a big disadvantage of analog power amplifiers - high amount of energy is transferred to heat. [2, 4, 16]

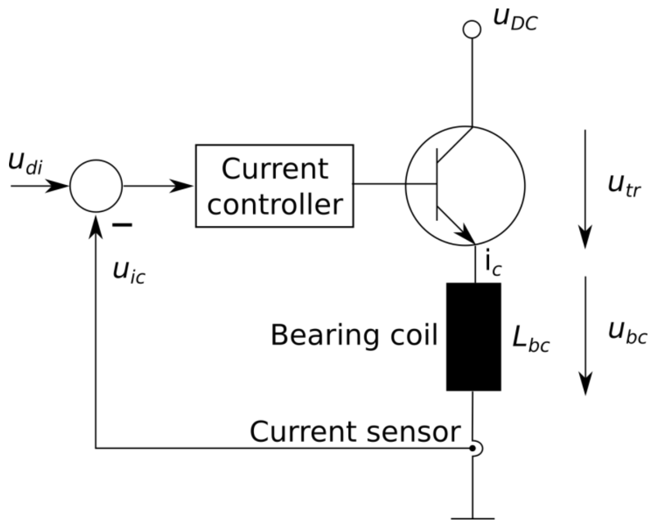


Figure 5 – Analog power amplifier principle

2.3.2. Switching power amplifiers

The switching power amplifiers switch between positive and negative voltage on given frequency (pulse width modulation - PWM) that results to alternating current in electromagnets. The switches are realized by transistors that are operated nonlinearly – transistors can only conduct or block the current. The energy loses are much smaller in comparison to analog amplifiers due to this nonlinear operation. [2]

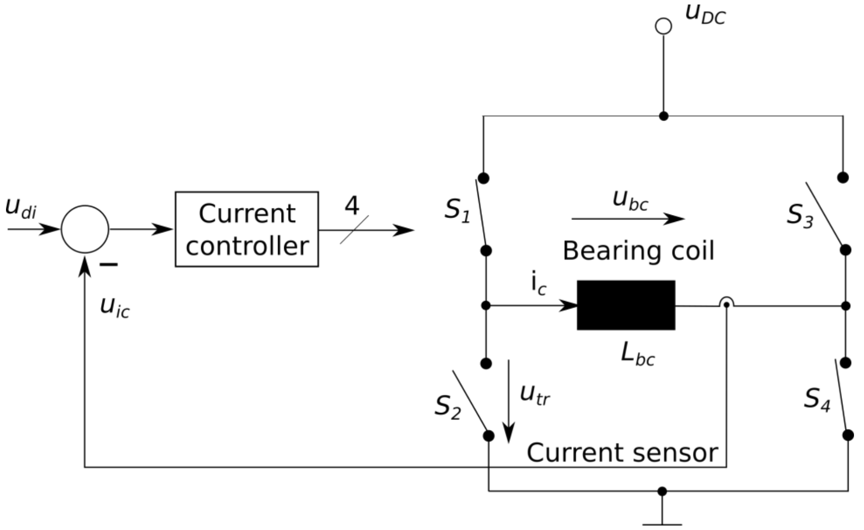


Figure 6 – Switching power amplifier principle

Because the direction of the bearing force has the same direction (depends on the squared current) that is independent on current direction in bearing coil, switching power amplifiers can be modified for only one current direction. This modification can be done by replacing two transistors (S_2, S_3) by diodes. These homopolar switched amplifiers are used in a large variety of AMB systems. [2]

Main disadvantage of switching power amplifier is alternating current output that cause remagnetization loss in the AMB. The higher is switching frequency, the lower are oscillations of current. Another way of reducing oscillations is to use passive filter between amplifier and bearing coil. [2, 16]

2.4. Control electronics

Next very important part of the AMB system is the hardware and software for information processing. Since early 1990's the control electronics are in most cases digital. Digital technology provides good flexibility in development, complex controller structures, all quantities can be monitored, calibration of the control parameters and cheap reproduction of the software. [2, 16]

The control system is responsible for dynamic behaviour of the rotor motion. Hardware of digital AMB control system commonly consist at least one microprocessor or digital signal processor (DSP), analog-to-digital (A/D) and digital-to-analog (D/A) converters, filters, memory, peripherals and other interfacing components. The following picture presents very rough structure of digital control system. [2, 16]

Figure 7 – Digital control

Measured data (e.g. position from deflection sensor) are sampled by A/D converter and are used as input of the control algorithm that runs on DSP. After calculation is the result converted by D/A converter into an analog form. This output signal from controller is fed to the power amplifiers. [2, 16]

The system can consist only one, powerful enough, single processor or can be based on multi-processor architecture with several processors. Each processor in this architecture is dedicated to its special task, e.g. pure levitation control, generating PWM patterns, tasks monitoring. [2, 16]

2.5. Bearing design

There are two main types of AMBs – radial and axial. Radial bearing provides support in two axis and axial bearing in only one axis. For the complete support of the shaft in all degrees of freedom, at least two radial and one axial bearing is needed. [2]

As mentioned, magnetic bearings are also added with back-up bearings that are not active in normal operation.

2.5.1. Radial bearings

There are two basic structural configurations of electromagnets in radial bearing. Difference between these two categories is made by distribution of magnet polarities around the rotor.

Radial bearing has **heteropolar configuration** if all the magnetic flux is perpendicular to axis of rotor rotation. The magnetic poles alternate with polarity around the rotor. Heteropolar configuration is showed on the following picture. [16]

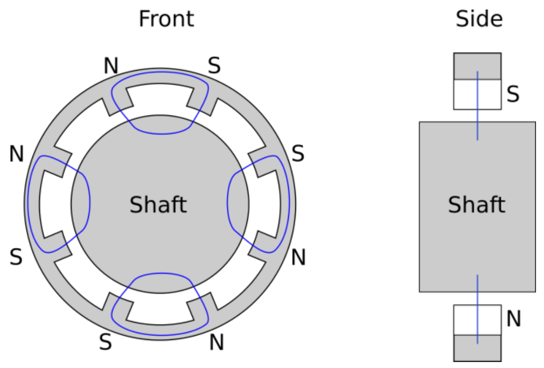


Figure 8 – Heteropolar configuration of radial bearing

To keep eddy current loss as low as possible, the magnetically active part of the rotor must be made from disk shaped layers of ferromagnetic sheets which are electrically insulated from each other – it must be laminated. The heteropolar configuration is usually the simplest and lowest cost solution.

In **homopolar configuration**, some amount of magnetic flux passes the rotor or stator axially. In this configuration there is less field variation around circumference of the rotor. Due to less field variation, the eddy current loss in rotating rotor is reduced. The homopolar configuration is mostly used with permanent bias field magnets. AMBs with homopolar configuration are usually more complicated and more expensive than with heteropolar configuration. [16]

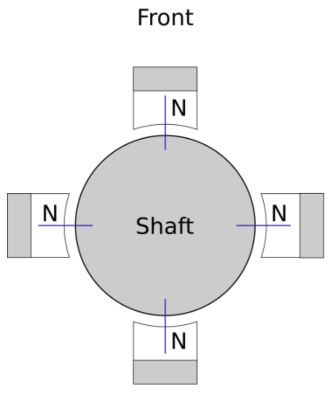
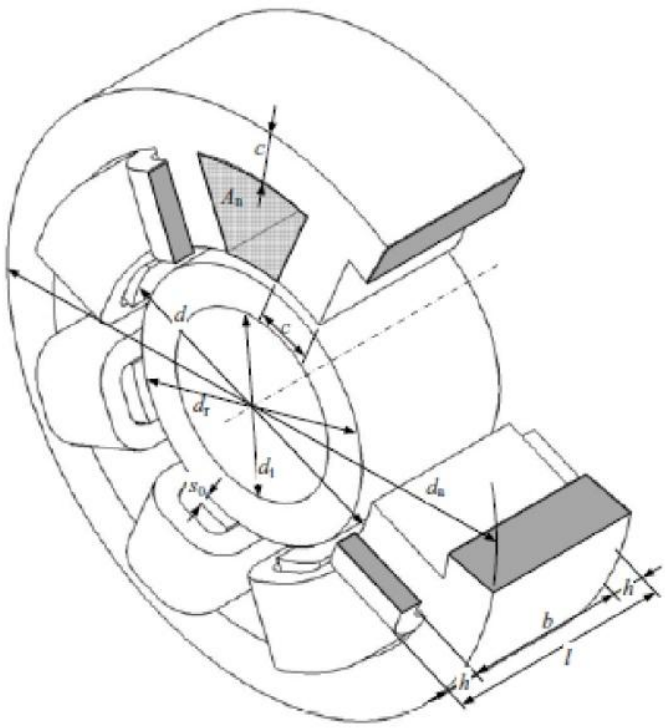


Figure 9 – Homopolar configuration of radial bearing

Radial bearing geometry in the following picture presents typical geometrical parameters of radial bearing with heteropolar configuration, that is more common than homopolar configuration. In real AMB the nominal air gap s_0 is much smaller than it is showed on the figure. [9, 16]



d	Inner diameter (bearing diameter)	d_a	Outer diameter
c	Leg width	d_i	Shaft diameter
h	Winding head height	b	Bearing width (magnetically active)
A_n	Slot cross section (winding space)	l	Bearing length
d_r	Rotor diameter	s_0	Nominal air gap

Figure 10 – Radial bearing geometry [16]

2.5.2. Axial bearing

Due to a support of only one axis, design of axial bearing is simpler than radial bearing. Axial bearing, sometimes called thrust magnetic bearing, consist two electromagnets operating in differential mode. The rotor have mounted disk that is placed between the two electromagnets. Following picture shows intersection of an axial bearing. [9, 16]

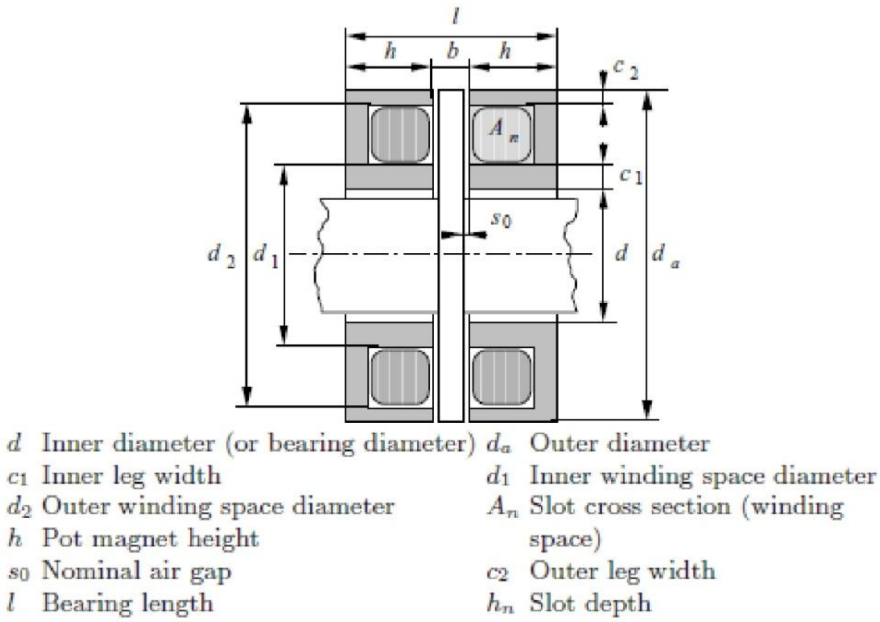


Figure 11 – Axial bearing geometry [16]

2.5.3. Backup bearings

Backup bearings, sometimes called touch-down, retainer or auxiliary bearings, are installed to avoid damage of rotor or stator, when the rotor touches its mechanical boundaries. This case can happen, for example, during electricity shutdown or AMB overload. Thus, the backup bearings are not active in normal operation and come to contact with rotor only in extraordinary situations. [6, 16]

Contact of rotating rotor and backup bearing leads in general to three typical states of motion (and their mixed forms). These states are oscillations of the rotor, chaotic jumping and backward whirl motion. Forward whirl motion can arise from touching unbalanced rotor to backup bearings. The most dangerous motion for the AMB system is the backward whirl motion. Creation of backward whirl is dependent on high friction coefficient between rotor and backup bearings. [11, 16]

In industrial application, commonly are backup bearings realized by ball bearings. Ball bearings provides low friction coefficient that reduce the risk of backward whirl. Beside the requirement on low friction, inner surface of backup bearing must be made from high strength material to avoid early wear, backup bearing should be kept clean from contamination, damping ribbons between outer ring and housing should be used and the time of operation on backup bearings should be as short as possible to avoid overheating.

3. Limiting characteristics and safety of AMBs

Like all other machines, AMB systems has also their own limiting characteristics such as load, size, stiffness, temperature, precision, speed, losses and dynamics. Besides of limit characteristics, customers are interested in safe and reliable products. [15, 16]

3.1. Load limitations

Carrying load is not only static behaviour, it has also dynamic requirements. Thus, load capacity of the AMB is dependent on the arrangement and geometry of electromagnets, magnetic properties of used materials, power electronics and on the control laws. Load limitations can be divided to two main limitation – “soft” limitation and “hard” limitation. [15, 16]

“Soft” limitation is related to winding cross section, mean winding length and available amount of cooling. These properties suggest that “soft” limitation is describing high static load limited by heat dissipation. This limitation can be reduced by a design that allows operate in high temperature. [15, 16]

“Hard” limitation arises from saturation of material by generated magnetic flux. During the saturation, carrying force has reached its maximal value and any force beyond “hard” limitation will cause the rotor touch the back-up bearings. This limitation can be improved by using cobalt-alloys with saturation flux density up to 2.4 T. Thus, bearing magnets can be designed for a specific load capacity up to 65 N/cm^2. [15, 16]

3.2. Speed limitations

Today’s rotational speeds in industry are in range from 3 kHz (grinding spindle) to 5 kHz (small turbo-machinery). Record in rotational speed is 300 kHz and it was reached in experiment for testing of material strength. Besides centrifugal load and critical bending speeds, there are limitations from eddy currents and hysteresis losses in magnetic material, air losses, requirements for power generation for the motor drive and heat dissipation for rotor (if it operates in vacuum). [15, 16]

Centrifugal load causes tangential and radial stresses in the rotor. The stress value has highest amplitude at the inner boundaries of the rotor disc. The tangential stress is even increased by laminated soft iron sheets that are added to the shaft. With the iron sheets made from amorphous metal (metallic glass) can shaft rotates up to 340 m/s in bearing area. Theoretical limit for amorphous metal is much higher (826 m/s). [15, 16]

To achieve operational rotation speed of the rotor, one or more **critical bending speeds** may be passed. Controller of AMB system has to enable stable and well-damped rotor behaviour with small displacements at the relevant rotor locations. In laboratory experiments it is possible to pass up to three critical elastic speeds. [15, 16]

3.3. Size limitations

There is no upper limit for bearing size, thus magnetic bearing can be designed for any load. Large bearings need special designs, where the bearing is separated into two halves, or single electromagnets are controlled individually. For example, AMB build by company S2M has rotor with a mass of 50 tons. [15, 16]

For the smallest bearings, that are used e.g. in medical instruments, the design of the AMB must be simplified. There are still fabrication limits to design micro magnetic bearings. [15, 16]

3.4. Temperature limitations

AMBs have big advantage against any kind of other types of bearings in high rotation speeds under high temperatures operations. High temperature AMBs (HT AMBs) can operate temperatures up to 800 °C, also speeds of 50000 rpm have been reached under temperature 600 °C. HT AMBs have special construction, e.g. ceramic coated copper windings, electrical connections made from silver, high temperature displacement sensors and other modifications. Functional tests of HT AMBs were successful, but actually available materials do not provide sufficiently long life time for long-term exposure to temperatures above 400 °C. Problems arise mainly from structural changes and deformations of used materials. [16]

3.5. Failure examples

The AMB have specific structure, as other typical mechatronic devices, consisting of mechanical, electrical and information processing parts. A failure can appear in each of these parts. **Software failures** are, for example, system breakdowns, run-time exceptions or incompatible program versions. **Electronics failures** can by caused by disturbances in signals, most often by noise from electromagnetic sources. The area of electro-magnetic compatibility considers high-powered switched amplifiers used in AMBs. **Mechanical failures** means break down of mechanical parts e.g. a blade loss, rotor crack or leakage of cooling system. [16]

4. Diagnostics of magnetic bearings

4.1. Objectives

The diagnostics program is used as an information-collecting tool for analysis of AMB system state during its operation or testing. It is possible to divide diagnostics into two main types. First type is a diagnostics of the shaft and AMB itself, e.g. deflection of shaft inside AMB or control currents in electromagnets. This part of diagnostics program uses Boolean limit flags for state definition and error recognition. The second type is a diagnostics of measuring and control equipment, e.g. diagnostic of offset or gain of used sensors. This type uses fuzzy logic to find errors.

The requirements on the diagnostics module are following:

a) Diagnostic module will be part of maglap++.
b) Diagnostic module is called in various time periods and with various quantity of measured data.
c) Diagnostic module must be able to diagnose overall state of given AMB system. Furthermore, the user of the diagnostics program has an option to choose what independent parts of the system will be diagnosed separately.
d) Diagnostic module returns information about states, errors and warnings, that can be displayed to user of android application.

4.2. Structure of diagnostic program

The diagnostic objected oriented program contains six modules that are necessary for shaft's state evaluation process. Five modules are used for diagnostics itself and are implemented directly in server side (maglap++). These modules are data managing module (DMM), variable preparation module (VPM), limit monitoring module (LMM), fuzzy logic monitoring module (FLMM) and state evaluation module (SEM). Each from this five modules is written in C++ language and is described in detail in following chapters of this work. Whole diagnostics program is composed from more than 6000 lines of code. The last module is android application written in Java language and it is used only for result displaying. This android application is used as a client and it communicates with maglap++. The diagram below shows basic structure of the diagnostic program.

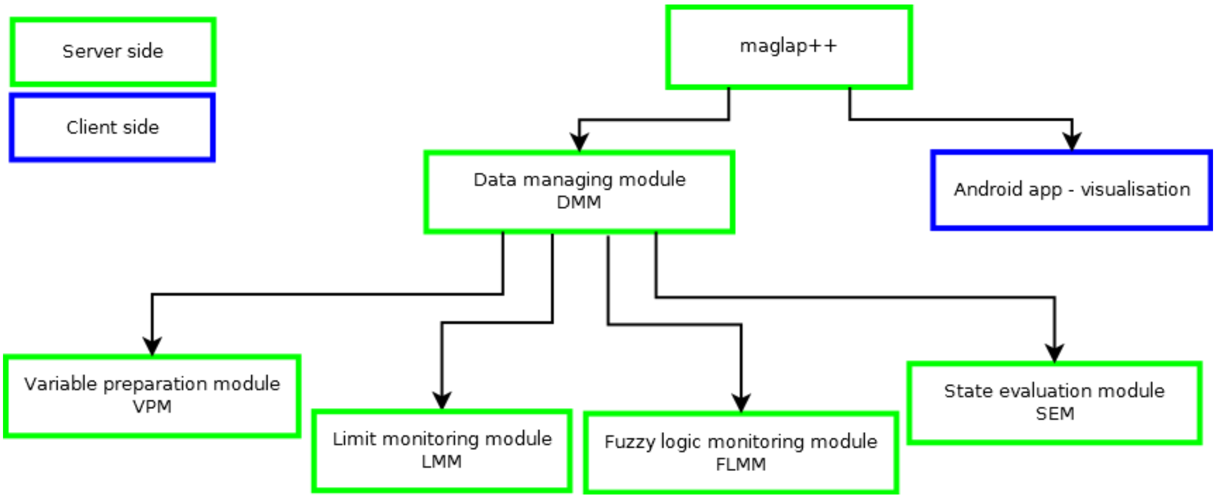


Figure 12 – Basic structure of the diagnostic program

The maglap++ program is communicating only with the DMM and with the android app. For following chapter is important only the part implemented to maglap++ (DMM with its sub-modules), android app module is described later in chapter 10.

5. Data managing module

The main module DMM (class *DaMa* in C++ code) is called by maglap++ with two parameters – structure of measured values (*MeVal* structure in C++ code) and structure of diagnostics (*Diag* structure in C++ code) These structures are essential for whole diagnostic program.

The main DMM's functions are:

- Checking if correct inputs are used
- Storage of processed data
- Calling functions of its sub-modules
- Communicating with maglap++

The measured data are received in *MeVal* structure, that includes pointers to all available measured data from given AMB system. The information about what parts of AMB system are going to be diagnosed are included in the *Diag* structure. Limit values for limit monitoring module and fuzzy sets for fuzzy logic module are loaded from configuration file. After receiving measured values and information about diagnostics, the DMM checks inputs by private method *DaMa::F_DaMa_CheckData* and then calls variable preparation module for preparation of needed values (e.g. mean and effective values of signals). These prepared variables are transferred to LMM and to FLMM for further processing. When all necessary information are collected from these two monitoring sub-modules, DMM sends the received information about AMB system to state evaluation module. State evaluation module computes general state of AMB system, errors and warnings. These information are collected in the state structure are returned back to DMM and further to maglap++. DMM adds to this structure also prepared mean values of signals that can be displayed to the user. Whole procedure is shown by the following diagram.

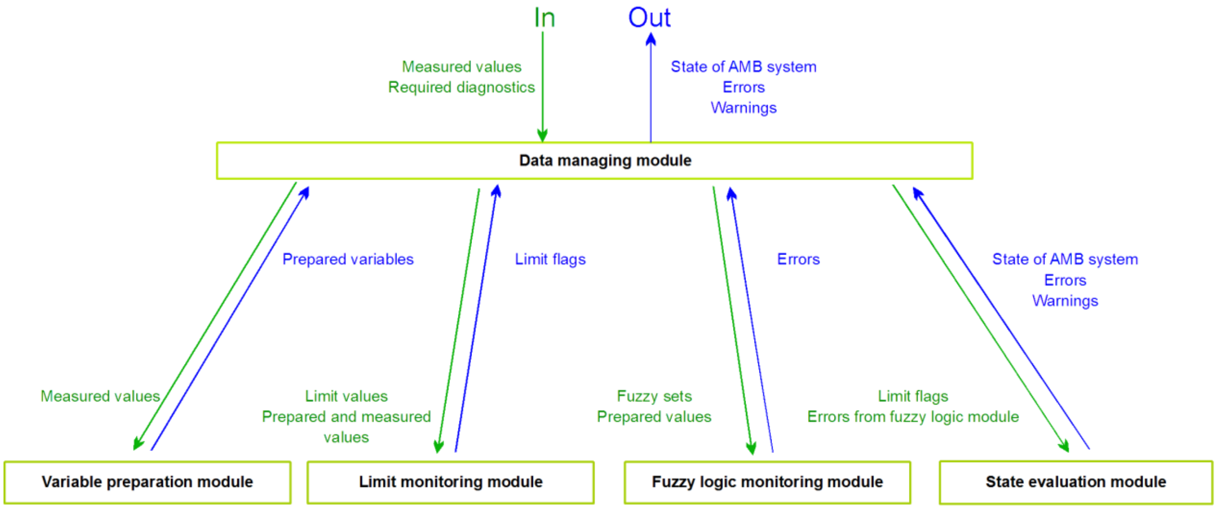


Figure 13 – Data managing module functions

5.1. Structure of measured values

The DMM is called in various time intervals when maglap++ collects enough measured data. The structure of measured values contains information about performed measurements and pointers to measured values of position, bias and control currents, speed of shaft and controller signals (voltage). The *MeVal* structure is shown on figure below. Position measurements are processed in micrometers, current in amperes, temperature in degrees Celsius and rotation in RPM.

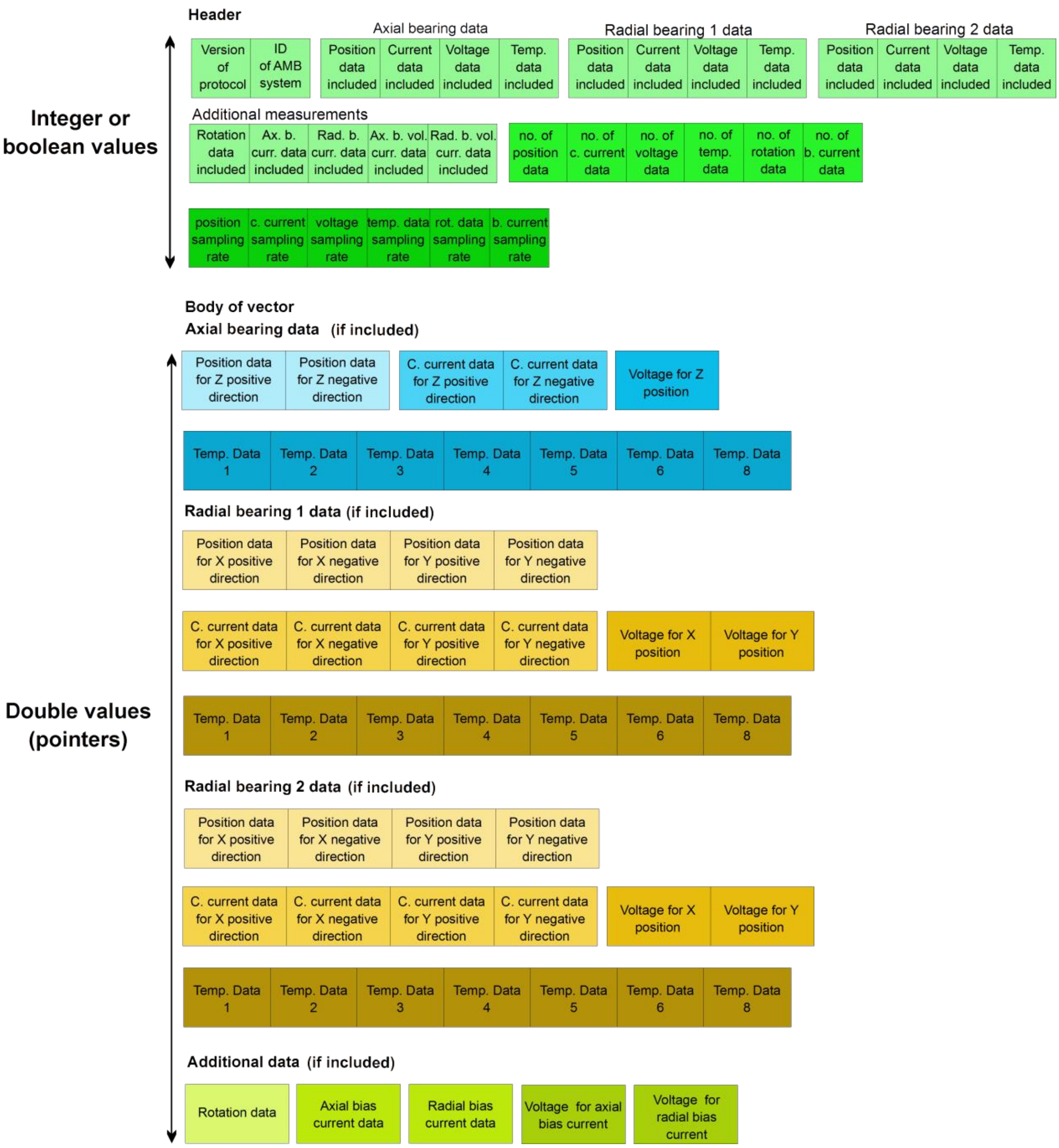


Figure 14 – Measured values structure (*MeVal*)

5.1.1. Header

Header part of the structure give us information about structure version, ID of the diagnosed AMB system, what measurements are done, number of measured samples and sampling rates for each measured value. There is an important assumption that *all similar measurements have the same sampling rate and number of measurements*. For example, all control current measurements have the same sampling rate and number of samples, all position measurements have the same sampling rate and number of samples etc. However, different types of measurement can have different sampling rates and number of samples, e.g. position sampling rate can be different from sampling rate of control current. ID of the AMB system give us information about what AMB system is monitored and also information about orientation of shaft. Horizontal shafts may have ID from 1 up to 100. Vertical shafts may have ID higher than 100. This conditions for shaft orientation identification can be easily modified in program code in class *StEv* (State evaluation module).

5.1.2. Body

Measured samples are stored in maglap++ memory. Body of the measured values structure contains pointers for these data. In first part of the body there are pointers for axial bearing measurements, second part and third part contains pointers for radial bearings and the last, fourth part contains pointers for additional measurements - bias currents and shaft's rotation speed.

Both axial and radial bearings have the same types of measurements. There are pointers for position measurements from each deflection sensor, control current measurements for each pair of coils, controller signal (voltage) for each axis and temperature for eight temperature sensor per bearing. Number of pointers for position, control current and voltage are doubled for radial bearing due to its construction difference to axial bearing.

5.2. Diagnostics structure

Diagnostics structure is much smaller than the *MeVal* structure and contains information about what parts of AMB system will be diagnosed and which diagnostics methods will be used. On the following figure there is shown the *Diag* structure.

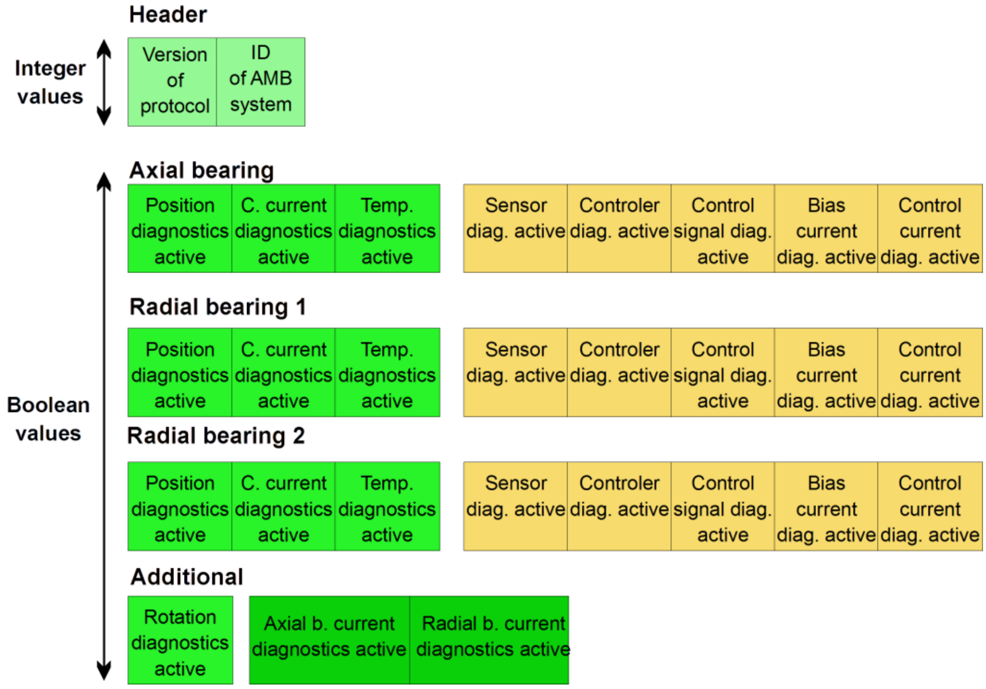


Figure 15 – Diagnostics structure (*Diag*)

Header in this structure includes only two values – version of the structure and ID of diagnosed AMB system. Body of the structure consist from Boolean values that can be divided into two types. Green highlighted diagnostics are processed by LMM and brown highlighted diagnostics are processed by FLMM. There can be called up to 27 diagnostics in the same time but every diagnostic method has different requirements on measured values.

5.3. Data managing

For almost every function of sub-modules it is necessary to prepare different input variables. It is also important to collect processed data from these modules. Input values (parameters) of methods have generally double, pointers for double and integer data types. Output values have generally double types or they are structures of different data types or vectors of Boolean values.

Communication with VPM

From the *Diag* structure it is known what variables have to be prepared by methods of VPM. These methods require pointers for measured signals, numbers of measurements and in some cases also sampling rates. Prepared variables are returned and saved in data structures. Later, the DMM uses prepared variables from these structures as an inputs for monitoring methods.

Communication with LMM

The DMM takes already prepared variables, pointers for measured samples and numbers of measurements as an parameters for diagnostic LMM's methods. The LMM's methods return *limit flags* in form of vectors. Every limit flag is an Boolean value relating to specific state or event in AMB. These vectors of Boolean values are merged together to only one vector that is stored in DMM by method *DaMa::F_DaMa_LfAll*.

Communication with FLMM

The FLMM's methods require prepared variables and fuzzy sets. As in case of communication with LMM are returned vectors of Boolean values. Every Boolean value in these vectors is related to specific error. These vectors are also merged to another large vector that is stored in DMM by method *DaMa::F_DaMa_FeAll*.

Communication with SEM

The SEM requires all limit flags and errors from the monitoring modules. Simultaneously with these two vectors is inserted also *Diag* structure. After processing of given data, SEM returns structure (*State* structure in the code) that includes state of AMB system, vector of all errors and vector of all warnings. Vectors of errors and warnings are now vectors of integer values – every error or warning has its specific ID.

Result returning to maglap++

The results from diagnostic program are returned in the result structure (*Result* structure in the C++ code). *Result* structure is composed of whole *State* structure from SEM and vector of mean values (*MeanVal* vector in the code) prepared by DMM itself. The result structure is shown on figure below.

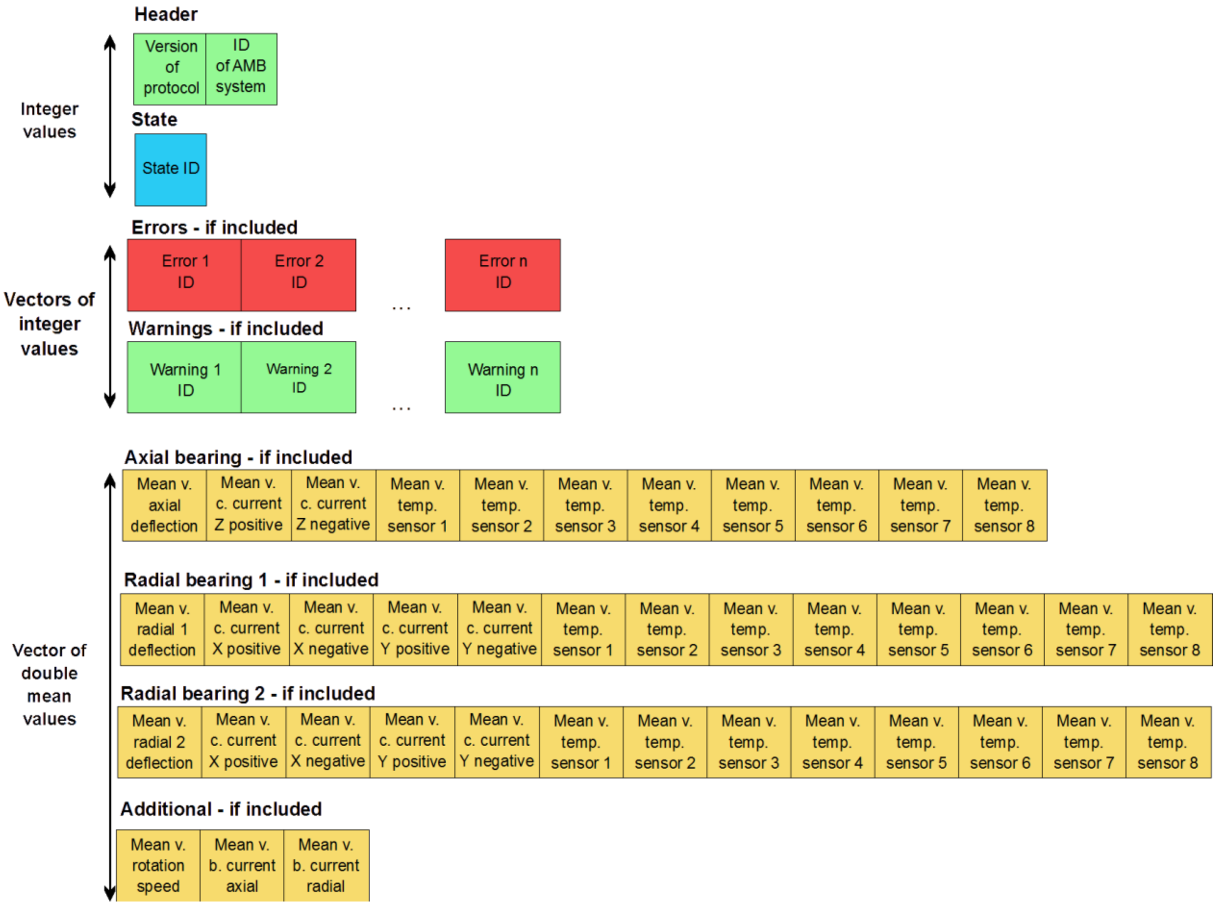


Figure 16 – Result structure (*Result*)

6. Variable preparation module

VPM (class *PreVar*) is used for calculation of values that cannot be read from *MeVal* structure directly. These values include, for example, mean values and effective values of alternating components (AC) of signals. Prepared variables are very important for further diagnostics made by LMM or FLMM, mean values are also displayed in android application. VPM also calculates position of the shaft from deflection signals.

6.1. Prepared variables

Most common variables that have to be prepared are mean values. Mean values of signals are calculated by following formula.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{6.1}$$

In the program code *n* is equal to number of samples for given signal and *x* is general sample.

Next very often prepared variable is effective value of alternating component of signal.

$$\tilde{x} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{6.2}$$

For calculation of effective value is necessary to already have prepared mean value of given signal. Variable *n* is again equal to number of samples for given signal. [7]

Limit monitoring needs only mean and effective values to be prepared. Fuzzy logic monitoring requires much more special variables that are described below.

With information about shaft position, bias and control currents in coils, it is possible to calculate force acting on shaft for each axis. For force calculation there is necessary to know more specific parameters of AMB than just measured data. Formula for force calculation were modified, following the example of Dr.-Ing. Gärtner's work.

$$F = K_1\left(\frac{(i_b+i_c)^2}{V_1+2(s_{nom}-s)} - \frac{(i_b-i_c)^2}{V_2+2(s_{nom}+s)}\right) \tag{6.3}$$

K_1 is coil constant, V_1 and V_2 are permeability and coil design dependent variables, s_{nom} is nominal air gap, s is position for given axis, i_b is bias current and i_c is control current for given axis. [7]

During preparation of force, algorithm must deal with possibility of different number of samples with different sampling rates for position, control and bias currents measured signals. When there is such a case of different number of samples or sampling rates, VPM firstly calculates time length for position and control current signals. Bias current value is not changing rapidly and for force calculation is used it's mean value. When the shorter time interval is known, program compares sampling rates. Final values that are inserted in formula 6.3 are values of position and control current that are closest to themselves in time domain. Following picture shows whole procedure.

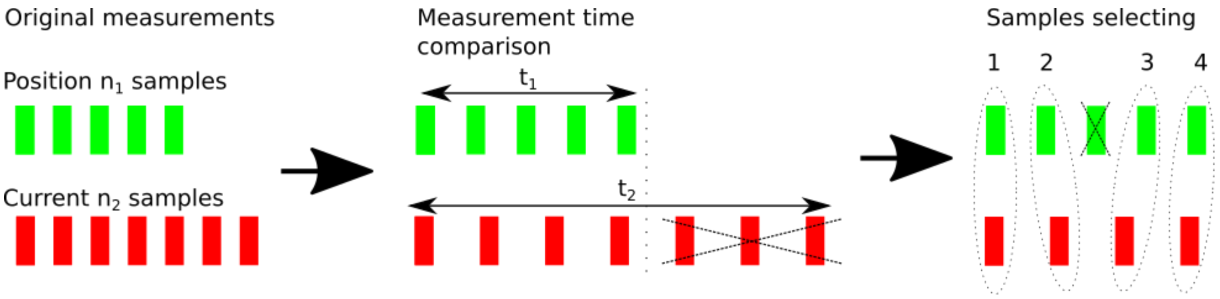


Figure 17 – Sample selection for force calculation

Another special values for fuzzy logic monitoring are ratios *W*, *R* and *A*. These rations are calculated from effective values of measured signals.

$$W = \frac{\tilde{i_c}}{\tilde{s}} \tag{6.4}$$

$$R = \frac{\tilde{s}}{\tilde{u}} \tag{6.5}$$

$$A = \frac{\tilde{u}}{\tilde{i_c}} \tag{6.6}$$

6.2. Position and deflection calculation

For each axis there are operating two opposite deflection sensors (showed on figure 3) where position can be calculated from formula 2.8. For deflection in axial bearing is this equation final because axial bearing supports shaft only in one axis. In case of radial bearing, shaft is supported by electromagnets in two perpendicular axis thus there are two pairs of deflection sensors. Formula 2.8 is used for calculation of position for X axis and for Y axis separately. By following equation are these two positions merged into one value – position deflection for whole radial bearing.

$$x_{Ra} = \sqrt{x_x^2 + x_y^2} \tag{6.7}$$

Merging X and Y positions to only one deflection value give us possibility to detect critical deflection between X and Y axis. On figure18 from chapter 7.2.1. Limit flags for axial and radial magnetic bearings are advantages of this operation displayed in detail.

7. Limit monitoring module

The main function of LMM is detection of critical or important values in processed signals. In C++ code is the LMM represented as *LiMo* class. The LMM monitors shaft deflection, currents in electromagnets, temperatures and rotation of the shaft by comparing measured values with limit values. Results of these comparisons is saved into Boolean limit flag variables. These limit flags are used for error, warning and general state identification.

Following table shows what types of diagnostics can be done by LMM and requirements on sensor connection (channels in maglap++). Details about limit flags are included in chapter 8.3.

Table 1 – LMM's diagnostic methods

Diagnostic type	Required signals/sensors	Groups of limit flags
Position diagnostics	**Axial bearing:** Two opposite position sensors for z axis **Radial bearing:** Two opposite position sensors for x axis Two opposite position sensors for y axis	Critical position Sensor over range Normal operation position Position in roller bearing Eff. value of position below limit
Control current diagnostics	**Axial bearing:** Control current sensor for z axis **Radial bearing:** Control current sensors for x axis Control current sensors for y axis	Minimal or zero control current Maximal control current Eff. value of c. current signal below limit
Temperature diagnostics	**Axial bearing:** Eight temperature sensors **Radial bearing:** Eight temperature sensors	Critical temperature Sensor error
Bias current diagnostics	**Axial bearing:** Bias current sensor **Radial bearing:** Bias current sensor	Maximal bias current Minimal or zero bias current
Rotation diagnostics	Speed sensor	Shaft is rotating Maximal speed Minimal or zero speed Shaft acceleration Shaft deceleration

Limit monitoring module returns limit flags in form of Boolean vectors back to DMM for each processed diagnostics.

7.1. LMM's inputs

Input data are composed of two important parts. After creation of instance of the class *LiMo*, method for reading limit values is called (method *LiMo::F_LiMo_LvRead*). These limit values are read from configuration file (appendix B) and are specific for given AMB system. These values, for example, include limit values for maximal currents in magnetic bearings, critical deflections of the shaft, etc.

The second data part contains actual measured data from the AMB system – pointers for measured data and prepared values. These values are imported for every diagnostic method separately. The measured data are in form that it is possible to compare these data directly with limit values from the first data set (the data are already recalculated from voltage to metric units).

7.2. Limit flags

When all required variables are prepared and diagnostic methods are selected, easy comparisons are done. Limit value from the first data part is compared to the selected measured or prepared value from the second data part. The results are saved as TRUE or FALSE values in Boolean limit flag variables.

There are three groups of limit flags (also limit values can be divided to three parts). First group are limit flags for axial bearing, second group are limit flags for radial bearings and last group are additional limit flags for monitoring of bias currents and shaft rotation. Limit flags for axial and radial bearings are very similar, but amount of limit flags is higher for radial bearing due to its construction. Some extra limit flags were added in comparison to dissertation work of Dr.-Ing. Gärtner, thus limit monitoring give us more detailed information about AMB state. Limit flags were also modified for application on "Magnet- und Fanglagerprüfstand" (MFLP) that uses separated coils for bias and control current. Bias current coils are connected in series for both radial bearings and also in axial bearing. Control current coils are operated differentially for each axis.

In the C++ code, the name of variable is created by several marks – "Vb" means Boolean variable, "lf" means limit flag, "p,i or t" is for position, current or temperature value, characteristic text, letter for bearing, letter for axis and one letter for its direction. For example variable *Vb_lf_iMinMean_az* means limit flag for minimal mean value of control current in coil of axial bearing, z axis. Whole list of limit flags is included in appendix A.

7.2.1. Limit flags for axial and radial magnetic bearings

As mentioned above, limit flags for axial and radial bearing are similar. These limit flags can be divided into few groups. In the first group there are limit flags for position diagnostics, in the second group there are flag variables for control current diagnostics and in the third group there are limit flags for temperature diagnostics.

Critical position limit flags (*Vb_lf_pCrit*) are set to TRUE when shaft deflection exceeds limit value for critical position. During processing is limit value compared to every measured position and the limit flag is set to TRUE if there is at least one critical measured position. Purpose of this limit flag is clear. For evaluation of critical position it is necessary to prepare position/deflection from deflection sensor signals. As mentioned in chapter 6.2 Position and deflection calculation, deflection for radial bearing is calculated differently from axial bearing deflection. This modification allows detection of critical position between two perpendicular axis. Due to construction of radial bearing it is possible to more accurate diagnose critical position in the direction of gravity (in case of horizontal shaft).

Sensor over range limit flags (*Vb_lf_pSensOver*) are used for detection of faulty signal from deflection sensors. There is sensor over range limit flag for every sensor in given bearing (two for axial bearing and four for each radial bearing). This limit flag is set to TRUE when signal from sensor has unrealistic value - it is higher or lower that limit values for given sensor. Evaluation of this limit flag is done for every sample in the signal. If there is at least one unrealistic value, flag is set to TRUE.

Position in normal working range limit flags (*Vb_lf_pInR*) are used for detection of shaft in normal working range. For evaluation of these flags are used mean deflections. TRUE value for this flag is set when shaft deflection is below its limit value.

Position in backup bearing limit flags (*Vb_lf_pRB*) give us information about shaft's physical contact to backup bearing. This limit flag is set TRUE when mean value of deflection exceeds distance of backup bearing from centre of bearing.

Effective value of position is minimal or zero limit flags (*Vb_lf_pAC*) are used for detection of movement (rotation) from position signals. These limit flags are set to TRUE when effective value of AC of the position is below limit e.g. when shaft does not spin. For radial bearing is selected highest effective value between AC of position for each axis and AC of absolute deflection from centre. This algorithm was chosen because effective value of AC of absolute deflection can be very small in case of rotation of position vector without changing its magnitude. In case of changing magnitude of position vector can be calculation of AC effective value of absolute deflection more sensitive than calculation of AC effective value of axis.

Position gradient too high limit flags (*Vb_lf_pG2H*) are used when change in shaft's position is too high for controller. Position gradient is calculated as difference between all consecutive pairs of samples multiplied by sampling rate. For radial bearing is again selected highest position gradient between gradients in each axis and gradient of magnitude of position vector.

Limit flags for position are displayed on picture below.

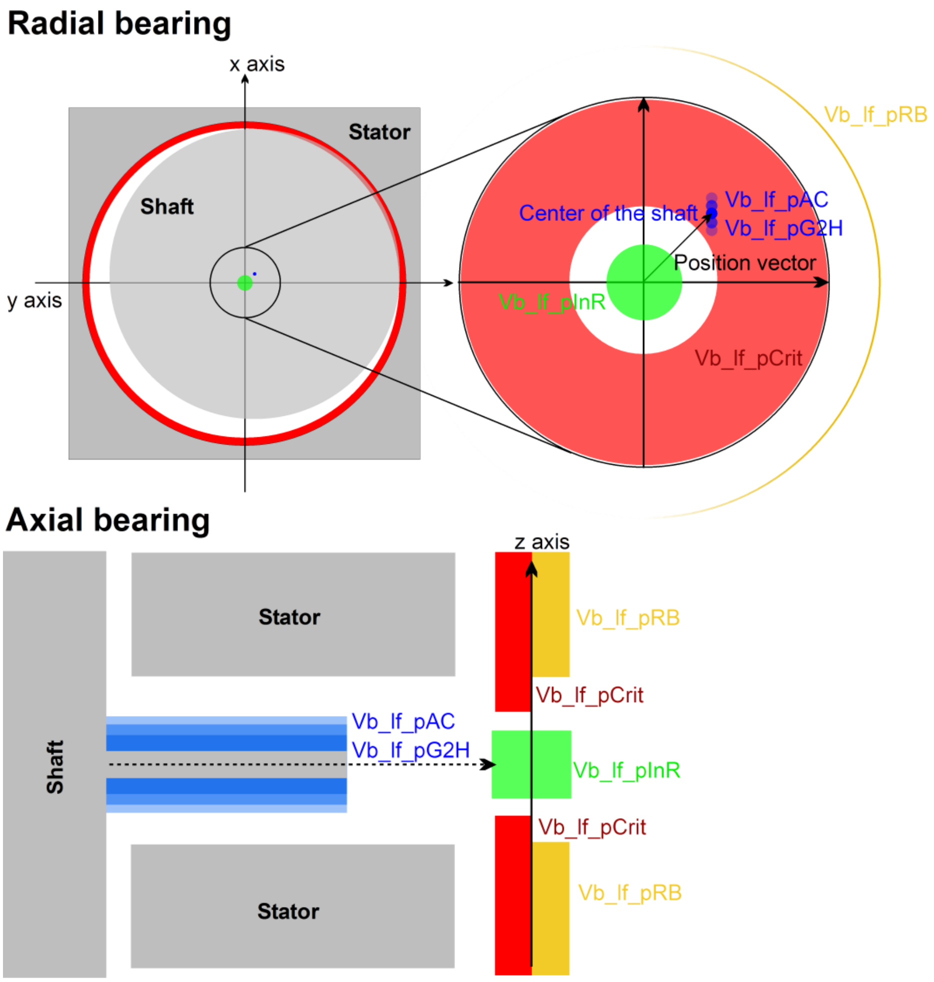


Figure 18 – Position limit flags

For control current limit flags, there is every time one limit flag from following groups for each coil in AMB.

Minimal or zero c. current limit flags (*Vb_lf_iMinMean*) are used for detection of turned off control current electromagnets, thus TRUE value is set when mean value of current is zero or nearly zero (noise in signal can cause small inaccuracies in mean value).

Maximal control current limit flags (*Vb_lf_iMaxMean*) are evaluated from mean value of control current. These limit flags are used for detection of current that can cause, for example, overheating of the coil. TRUE value is set when mean value of the current is higher than its limit value.

Effective value of control current is minimal or zero limit flags (*Vb_lf_iAC*) are dependent on shaft rotation. These limit flags are set to TRUE when effective value of AC of control current is below its limit.

Critical control current limit flags (*Vb_lf_iCrit*) are similar to maximal control current limit flags. The difference is that critical control current is checked for every measured sample, thus critical peak values of the current can be detected.

Temperature diagnostics limit flags

Every temperature sensor is connected to two limit flags from following groups.

Maximal temperature limit flags (*Vb_lf_t1-8Max*) depends on mean value of temperature. TRUE value is set when temperature exceed its limit value.

Temperature sensor error limit flags (*Vb_lf_t1-8SensError*) are used for detection of faulty temperature signal. These limit flags are set to TRUE when temperature is higher or lower than given limit values or if the change in values between two measurements is unrealistically high.

7.2.2. Additional limit flags

There are few more limit flags that does not depend on position, control current or temperature in ABMs. These limit flags give us information about shaft rotation and bias current.

Limit flags "**too high speed of shaft**, **too low speed of shaft** and **shaft is not rotating**" (*Vb_lf_n2H*, *Vb_lf_n2L* and *Vb_lf_n0*) are used for monitoring of shaft's rotation and are calculated from mean rotation values.

Acceleration and deceleration of the shaft is monitored by limit flags "**shaft is accelerating** and **shaft is decelerating**" (*Vb_lf_nAcc*, *Vb_lf_nDec*). Acceleration is calculated by VPM as difference between mean value of rotation in first half of data and mean value of second half. This difference value is divided by time of whole measurement.

In given AMB system are two bias currents, one for axial bearing and one for radial bearings.

"**Maximal bias current** and **minimal or zero bias current**" limit flags (*Vb_lv_iBMaxMean*, *Vb_lv_iBMinMean*) are evaluated from mean value of bias current and are used for detection of high bias currents and turned off bias current coils.

Critical bias current limit flags (*Vd_LiMo_lv_iBMax*) detects high peak values in bias current signal and can be used for protection of electronics.

7.3. Modification of limit monitoring

7.3.1. Addition and changes of limit values

Changing of limit values can be done in configuration file that is described in appendix B. Adding of new limit values requires changes in configuration file, *DaMa* class, *LiMo* class and *structs* header. At first limit value must be created in configuration file and read by *DaMa* class by method *DaMa::F_DaMa_ReadLV*. Limit value (double type) is stored in structure *R_LV* that can be modified in *struct* header file. LMM (*LiMo* class) gets the limit value from DMM by calling *LiMo::F_LiMo_LvRead* method.

7.3.2. Adding new limit flag

Limit flag can be added easily in *LiMo* header file as an private Boolean variable. Limit flags are returned by public functions of class *LiMo* in form of Boolean vectors. It is very important to *keep order of limit flags in vectors and to know length of the vectors*. Changes in method *StEv::F_StEv_LFLengthRead* are necessary. Specific requirements are described more in detail in chapter 9.1 SEM's inputs.

7.3.3. Adding new limit monitoring method

Addition of new diagnostic method can be done in class *LiMo* where the method should be private. Public methods are used for calling of groups of diagnostics methods, e.g. all position diagnostics for given bearing. Example of public method is *LiMo::F_LiMo_PosAxZDiag* that is called for position diagnostics of axial bearing. Every public method returns vector of Boolean values – limit flags. As an example of the vector of limit flags is *Vvb_LiMo_LfPosAx* that contains position limit flags for axial bearings and it is returned to DMM. New method should add its values only on the end of these vectors, e.g. by function *vector::push_back*.

8. Fuzzy logic monitoring module

FLMM (class *FuzMo*) is mainly used for diagnostics of sensors and control equipment of AMB system. In some cases FLLM serves as more sensitive detection of errors than LMM, for example in bias current diagnostics. As the name of the module implies, it is used fuzzy logic to detect errors. Following table shows types of diagnostics that can be done by FLMM and requirements for channel connections for each diagnostic method. FLMM is used for diagnostics of each axis separately, that means, for axial bearing are diagnostic methods called only once (for z axis) and for radial bearing twice (once for x axis and once for y axis).

Table 2 – Table of FLMM diagnostics

Diagnostic type	Signals needed	Errors
Deflection sensors diagnostics	Positive axis deflection signal Negative axis deflection signal Control current signal Bias current signal (axial or radial, depends on AMB) Control signal (voltage) of the axis	ES1P – Positive offset of sensor signals ES1N – Negative offset of sensor signals ES2P – Increased gain of sensors ES2N – Reduced gain of sensors
Controller diagnostics	Positive axis deflection signal Negative axis deflection signal Control signal (voltage) of the axis	EC1P – Increased gain of controller EC1N – Reduced gain of controller EC2P – Increased set point of controller EC2P – Reduced set point of controller
Control signal diagnostics	Positive axis deflection signal Negative axis deflection signal Control current signal Control signal (voltage) of the axis Bias current signal (axial or radial, depends on AMB)	ECS1P – Positive offset of control signal ECS1N – Negative offset of control signal ECS2P – Increased gain of control signal ECS2N – Reduced gain of control signal
Bias current diagnostics	Control signal (voltage) of the axis Bias current signal (axial or radial, depends on AMB)	EBC1P – Positive offset of bias current EBC1N – Negative offset of bias current
Bearing current diagnostics	Control signal (voltage) of the axis Bias current signal (axial or radial, depends on AMB)	ECC1P – Positive coil bearing current positive offset ECC1N – Positive coil bearing current negative offset ECC2P – Negative coil bearing current positive offset ECC2N – Negative coil bearing current negative offset

Groups of error values are returned in form of Boolean vectors back to DMM.

8.1. FLMM's inputs

As in case of LMM, there are also two groups of input data. First group includes prepared variables from VPM and the second group includes fuzzy sets (*FuzzySet* structures in program code). Functions of FLMM take prepared value and calculate its membership value for three membership functions – *big, normal* and *small*.

There are two requirements on membership functions. First requirement is that membership functions are trapezoidal. This requirement is important for division of the function to few linear parts. Second requirement that have to be fulfilled, is that sum of these three functions is equal to one for each input value. When the fuzzy set meet these requirements it is possible to *describe any fuzzy set by only four numbers* – intersection of x axis coordinates with 0 and 1 value of membership.

Every "small" or "big" membership function is divided to three intervals. For "small" membership function, the first part has always membership value equal to one and it is interval from minus infinity to the point where the membership value of the function starts to decrease. Coordinate of x axis of this point is also the first number used for fuzzy set description. Second part of "small" membership function is linearly decreasing interval. This interval starts on the end of the first interval and ends in point, where the function falls to zero value. The x coordinate of this second point is the second number used for fuzzy set description. The "big" membership function consist of similar intervals as the "small" membership function, but its first interval starts on zero value and the last interval ends on membership value of one. In program code are first and last intervals defined by simple IF conditional statement. For example:

IF (measured_value < first_description_number) THEN small_membership_value = 1

IF (measured_value > second_description_number) THEN small_membership_value = 0

The middle intervals have different slopes and for the membership calculation it is used formula of linear function.

$$y = ax + b \qquad (8.1)$$

Nevertheless coefficients *a* and *b* are unknown and must be calculated. As mentioned above, every fuzzy set is described by four numbers. Two numbers are for description of "small" membership function and two numbers for “big” membership function. We can use formula for calculation of linear function through two points.

$$y = y_1 + \frac{y_2 - y_1}{x_2 - x_1}(x - x_1) \tag{8.2}$$

Where y_1 and x_1 are coordinates of first point and y_2 with x_2 are coordinates of the second point. We know that y_1 coordinate is always equal to one and y_2 coordinate is always equal to zero (for “small” membership functions). We can put these values into the equation and after few modifications we get following form of the equation:

$$y = x\left(-\frac{1}{x_2 - x_1}\right) + \frac{x_1}{x_2 - x_1} + 1 \tag{8.3}$$

Now coefficient a and coefficient b can be calculated.

$$a = -\frac{1}{x_2 - x_1} \tag{8.4}$$

$$b = \frac{x_1}{x_2 - x_1} + 1 \tag{8.5}$$

The last membership function of the fuzzy set give us information about “normal” membership value. From the second requirement it is known that sum of values of all membership functions is equal to one for each input value. So it is possible to calculate “normal” membership value as:

$$N\ = 1 - B - S \tag{8.6}$$

Where N, B and S are membership values of “normal, big and small” membership functions.

Figure below displays fuzzy set of “small, normal and big” membership functions with highlighted important points (fuzzy set description numbers).

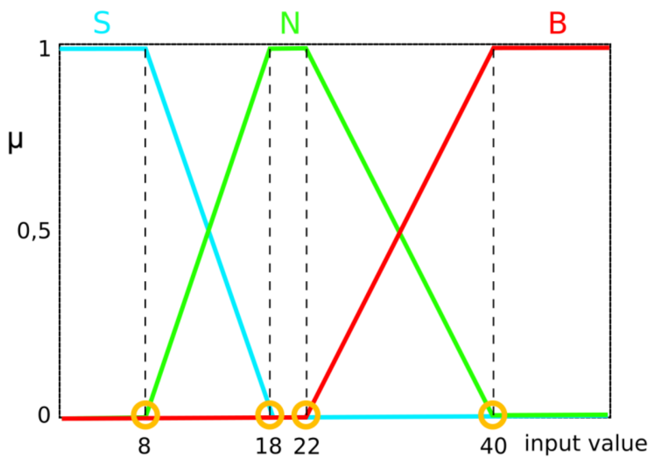


Figure 19 – Fuzzy set with highlighted description numbers

In this example, description numbers of fuzzy set are 8, 18, 22 and 40. Fuzzy sets are specific for every AMB system and must be selected with professional knowledge of the system.

8.2. Fuzzy logic monitoring error evaluation

For the error detection are used same rules as in dissertation work “Neuartige Verfahren für die Überwachung und Diagnose von aktiv magnetgelagerten rotierenden Maschinen“ from Dr.-Ing. Seffen Gärtner. Names and groups of errors are slightly modified for this diploma thesis. During calculation are used fuzzy operators described in theoretical part of this work.

Following the ideas of Dr.-Ing. Gärtner’s no defuzzification in sharp output is done. Errors are evaluated directly from degree of fulfilment (membership value) by use of threshold value. Threshold can be modified in configuration file (*Vd_DaMa_ErrThreshold* variable). [7]

Error evaluation rules for deflection sensor diagnostics

ES1P/N – Positive/negative offset of signal from deflection sensors

ES2P/N – Increased/reduced gain of the deflection sensors

WHEN $\bar{F} = B$ THEN *ES1P* = *TRUE*

WHEN $\bar{F} = S$ THEN *ES1N* = *TRUE*

WHEN $W = N$ AND $\bar{\iota}_c = N$ AND $\tilde{F} = S$ THEN *ES2P* = *TRUE*

WHEN $W = N$ AND $\bar{u} = N$ AND $\tilde{F} = B$ THEN *ES2N* = *TRUE*

Error evaluation rules for controller diagnostics

EC1P/N – Increased/reduced gain of the controller

EC2P/N – Increased/reduced set point of the controller

WHEN $R = S$ THEN *EC1P* = *TRUE*

WHEN $R = B$ THEN *EC1N* = *TRUE*

WHEN $\bar{s} = S$ THEN *EC2P* = *TRUE*

WHEN $\bar{s} = B$ THEN *EC2N* = *TRUE*

Error evaluation rules for control signal diagnostics

ECS1P/N – Increased/reduced offset of the control signal

ECS2P/N – Increased/reduced gain of the control signal

WHEN $\bar{u} = S$ AND $\bar{\iota}_c = N$ AND $I_B = N$ AND $\bar{F} = N$ THEN *ECS1P* = *TRUE*

WHEN $\bar{u} = B$ AND $\bar{\iota}_c = N$ AND $I_B = N$ AND $\bar{F} = N$ THEN *ECS1N* = *TRUE*

WHEN $I_B = N$ AND $A = S$ THEN *ECS2P* = *TRUE*

WHEN $I_B = N$ AND $A = B$ THEN *ECS2N* = *TRUE*

Error evaluation rules for bias current diagnostics

EBC1P/N – Increased/reduced offset of bias current

WHEN $\bar{u} = N$ AND $I_B = B$ THEN *EBC1P* = *TRUE*

WHEN $\bar{u} = N$ AND $I_B = S$ THEN *EBC1N* = *TRUE*

Error evaluation rules for bearing current diagnostics

ECC1P/N – Increased/reduced offset of positive coils of magnetic bearing

ECC2P/N – Increased/reduced offset of negative coils of magnetic bearing

WHEN $\bar{u} = S$ AND $I_B = B$ THEN *ECC1P* = *TRUE*

WHEN $\bar{u} = B$ AND $I_B = S$ THEN *ECC1N* = *TRUE*

WHEN $\bar{u} = B$ AND $I_B = B$ THEN *ECC2P* = *TRUE*

WHEN $\bar{u} = S$ AND $I_B = S$ THEN *ECC2N* = *TRUE*

8.3. Modification of fuzzy logic monitoring

8.3.1. Addition and changes of fuzzy sets

Changes in fuzzy sets are done by description numbers included in the configuration file. Description numbers can be identified by variables ending on:

S0 – Point where the "small" membership starts with 0 value

S1 – Point where the "small" membership ends with 1 value

B0 - Point where the "big" membership ends with 0 value

B1 – Point where the "big" membership starts with 1 value

Addition of new fuzzy set requires changes in the configuration file and *DaMa* class. In configuration file should be created new description points that are read in DMM by *DaMa::F_DaMa_ReadFS* method. New fuzzy set should be saved in new *FuzzySet* structure.

8.3.2. Addition of new fuzzy logic monitoring method

New method can be added in *FuzMo* class and called directly by DMM. These public methods of *FuzMo* class are also returning vectors of Boolean values thus it is also *very important to keep order of variables and to known length of the vectors* for state evalueation. Changes in method *StEv::F_StEv_LFLengthRead* are necessary. Example of diagnostic method is *FuzMo::F_FuzMo_SensDiag*. New boolean variables should be added on the end of *Vvb_DaMa_FeAll* vector by *DaMa::F_DaMa_FeAll* method.

Essential private methods for fuzzy monitoring are *FuzMo::F_FuzMo_SNBMemb*, *FuzMo::F_FuzMo_FuzzySum* and *FuzMo::F_FuzMo_EvaErr*. *FuzMo::F_FuzMo_SNBMemb* is used for calculation of membership values for small, big and normal membership functions. *FuzMo::F_FuzMo_FuzzySum* is used only when summing of membership values is necessary and *FuzMo::F_FuzMo_EvaErr* returns final value if there is an error or not.

9. State evaluation module

When all data are processed by preparation and monitoring modules, results from these modules are inserted into SEM (class *StEv*). Besides state evaluation from limit flags, the SEM creates error and warning vectors. After all calculations SEM returns *State* structure back to DMM.

9.1. SEM's inputs

Input parameters are limit flags vector, fuzzy errors vector and *Diag* structure. Order of limit flags and fuzzy errors in vectors is very important for correct reading. Lists of limit flags and fuzzy errors orders are listed in appendix C.

Every diagnostic type has specific length and order of Boolean values in the vectors. If there is active an diagnostics, limit flags or fuzzy error vector is enlarged by specific number. That means, if no diagnostics is active, than the limit flags and fuzzy errors vectors have size equal to zero. These specific lengths are defined by method *StEv::F_StEv_LFLengthRead*. During reading of limit flags and fuzzy errors are created indexes that points on beginning of groups of limit flags or fuzzy errors. First index is every time equal to 0 and following indexes are calculated by formula:

$$i_n = i_{n-1} + d_{n-1} * l_{n-1} \tag{9.1}$$

Where i_n is the index for given group, i_{n-1} is index of previous group in the vector, d_{n-1} is value from diagnostics vector (it is Boolean value – can be equal to 0 or 1 only) and give us information if there are limit values for previous diagnostics or not and l_{n-1} is length of previous group of limit flags.

For finding concrete limit flag or fuzzy error position in the vector is taken index value of specific group (e.g. temperature limit flags for radial bearing 1) and added known position of limit flag or fuzzy error from given order. For better understating, following figure shows limit flag and fuzzy error reading procedure.

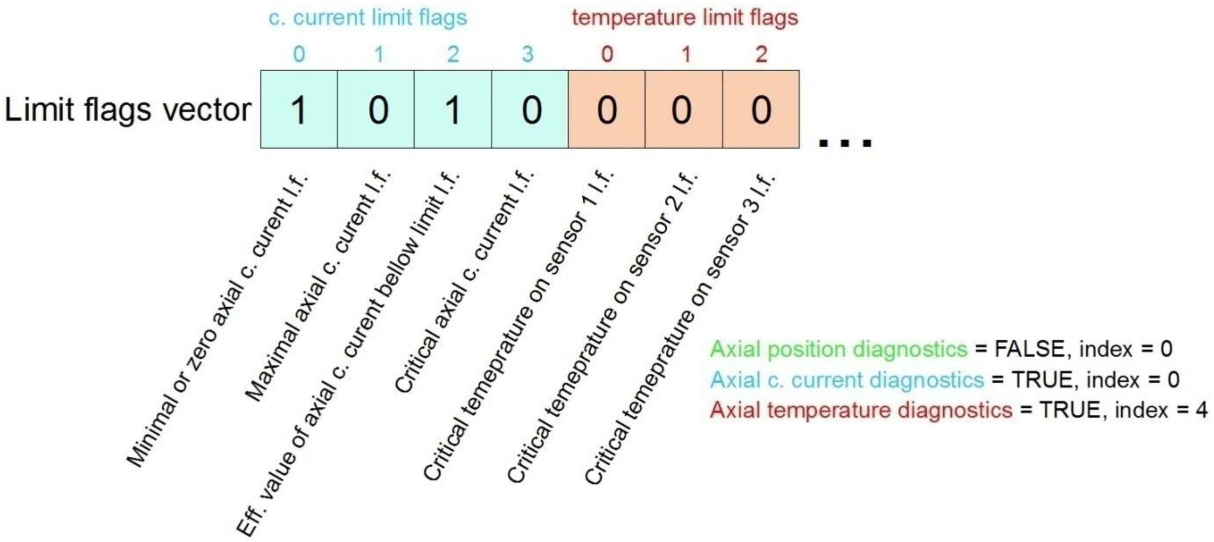


Figure 20 – Limit flags reading algorithm

Order of limit flags begins with axial position limit flags, second are axial control current limit flags, third are axial temperature limit flags etc. For given example are indexes and limit flags positions calculated as follows:

Axial position limit flags group index is first in the vector, so it is equal to 0.

Axial control current limit flags group index is calculated by formula 9.1 where i_{n-1} is equal to 0 (axial position diagnostics index). Length l_{n-1}, defined by method *StEv::F_StEv_LFLengthRead*, is equal to 7. But axial position diagnostics is not active so d_{n-1} is equal to 0. Resulting index for axial control current diagnostics is 0. For example when critical axial c. current limit flag is going to be read, control current index is summed with position of the limit flag and result is position in vector equal to 3.

Variables in formula 9.1 for calculation of axial temperature limit flags group index are i_{n-1} equal to 0, d_{n-1} is equal to 1 and l_{n-1} is equal to 4. Resulting index is then 4.

9.2. Error and warning detection

Error detection is used only with limit flags, because FLMM results are already detected errors. Errors and warnings are detected by simple Boolean operations with combination of IF statement conditionals.

In the most of cases specific limit flag express directly specific error. Only for critical position error identification are rules changed. As an example is described axial critical position error identification algorithm.

The axial critical position error detection starts when SEM receives limit flag with information that there is critical position measured. One must realize that critical position does not always mean error state, for example, when shaft is lying on the backup bearings without any movement. Conditions when the position error is considered as existing are:

1) There is critical position measured and there are non-minimal control currents in coils. (Control current measurements are necessary for given AMB)
2) Or there is critical position measured and the shaft is rotating. (Rotation measurements are necessary)
3) Or there is measured critical position and we do not have any information about control currents or rotation. (We cannot distinguish between error state and shaft lying in backup bearings)

In the diagnostic program is implemented identification of only four warnings. Three of them are very similar and they express position of shaft is out of normal working range but the deflection is not so big to activate critical position error. Fourth warning is set to active when shaft has low rotation speed. This warning is suppressed when the shaft is accelerating, decelerating or not rotating.

9.3. Error and warning IDs

Every error or warning has its unique ID that will be displayed to user of android application. There is 170 errors that can be detected, 80 errors can be detected from limit flags and 90 errors can be detected by FLMM. List of warnings is much smaller, there are only four warnings that can be detected. Complete lists of errors and warnings are in appendix D.

Every error or warning ID is composed from five digits. These digits carry information about which module detected the error (FLMM or LMM, respectively detected from limit flags), information about position in AMB system and information about type of error or warning.

The first digit carries information about if it is error or warning and where is the origin of detection.

Table 3 – First digit in error/warning ID

Digit	Meaning
1	Error detected from limit flags
2	Error from FLMM
3	Warning detected from limit flags

The second digit give us information about what AMB is in error or warning condition.

Table 4 – Second digit in error/warning ID

Digit	Meaning
1	Error/warning in axial bearing
2	Error/warning in radial bearing 1
3	Error/warning in radial bearing 2
4	Error/warning is not in bearing (e.g. speed is too high)

The third digit give us information about type of error or warning. Meaning of third digit is different between errors or warnings detected from limit flags and errors or warnings from FLMM.

Table 5 – Third digit in error/warning ID, limit flags

Digit	Meaning
1	Position error/warning
5	Control current error/warning
3	Temperature error/warning
4	Rotation error/warning
5	Axial bias current error/warning
6	Radial bias current error/warning

Table 6 – Third digit in error/warning ID, FLMM

Digit	Meaning
1	Deflection sensors error/warning
5	Controller error/warning
3	Control signal error/warning
4	Bias current error/warning
5	Control current error/warning

Digit 4 and 5 are used for specific errors/warnings identification and description table cannot be well-arranged. Below are listed examples of errors and warnings.

11110 – Critical position of shaft in axial bearing

11122 – Sensor over range in positive sensor of Z axis in axial bearing

23231 – Increased gain of controller for Y axis of radial bearing 2

32110 – Position of shaft is not in normal working range in radial bearing 1

9.4. State evaluation

SEM shows the result as one of nine different states. Every state has its special ID that is transferred to android application and displayed to user as a text message on main screen. State evaluation is done by IF conditional statements. Following list of states is ordered by state priority, e.g. if there is error and warning in one time, result is error state, because it has higher priority than warning state.

Error state

Priority: 1 State ID: 100

Error state has highest priority and it is active when there is at least one error detected.

Condition:

Size of error vector is larger than zero.

Warning state

Priority: 2 State ID: 200

Warning state has second highest priority and it is active when there is at least one warning detected.

Condition:

Size of warning vector is larger than zero.

Not enough data state

Priority: 3 State ID: 300

Not enough data state is active when there is no error or warning detected, but there is not enough information to evaluate general state of AMB system. For example if there is active only control current diagnostics without any errors or warnings detected and we have no information about shaft position, rotation etc., not enough data state is set to active.

Conditions:

If there is at least one inactive diagnostics from all position diagnostics (LMM's position diagnostics for axial, radial 1 and radial 2 bearing)

OR at least one inactive diagnostic from all control current diagnostics

OR inactive rotation diagnostic.

Shaft lies on backup bearings state

Priority: 4 State ID: 401

Shaft lies on backup bearings state is active when the shaft lies on backup bearing without any movement and control current in all coils is zero or minimal. Evaluation of this state needs information about if given AMB system is vertical or horizontal. This information is read from AMB ID.

Conditions:

AC effective value of position and AC effective value of control current in every bearing is below limit

AND control current in every bearing is zero or minimal

AND shaft is touching backup bearings (touches axial backup bearing for vertical shaft or touches radial backup bearings for horizontal shaft).

Standby state

Priority: 5 State ID: 402

Standby state is active when the shaft levitates in normal working range but does not rotate.

Conditions:

Position of shaft is in normal working range in all bearings

AND shaft does not rotate.

Accelerating state

Priority: 6 State ID: 403

Accelerating state is active when the shaft is accelerating.

Condition:

Shaft is accelerating.

Decelerating state

Priority: 7 State ID: 404

Decelerating state is active when the shaft is decelerating.

Condition:

Shaft is decelerating.

Normal operation state

Priority: 8 State ID: 405

This state is active when the AMB system is working in normal operation – shaft is levitating and rotating under normal working conditions.

Conditions:

Position of shaft is in normal working range in all bearings

AND NOT shaft does not rotate.

Transient state

Priority: 9 State ID: 500

Transient state is implemented only for safety reasons and it is active only when information about AMB system does not fit to any previous state. In ideal case, transient state will be never active or only in rare cases.

Condition:

State does not fit to any previous conditions.

Evaluation of states with IDs 401, 402, 403, 404 and 405 can be started only when there are active LMM's diagnostics for position and control current in *all* magnetic bearings and rotation diagnostics.

10. Android visualisation app

The android visualisation app (AMBVisu1) is an object oriented program written in Java language and it is used for displaying of results from diagnostic program. This client side program consists of approximately 2000 lines of code. The app is composed of four activities (screens with GUI) added by background tasks.

10.1. Graphical layout

Graphical layout is optimized for displays with resolution starting at 480 x 800 pixels so it can run even on older android smart phones. Main activity's (class *MainActivity*) window includes text field where the state of AMB is displayed (TextView *status_bar*), three buttons for entering windows with measured values (*AxButton*, *Ra1Button* and *Ra2Button*), event log for displaying messages from diagnostic program (*listView*) and button for cleaning of event log (*AcknButton*). On the top of the screen are added information about AMB ID and rotation speed. Activities for displaying of measured values (classes *AxialActivity*, *Radial1Activity* and *Radial2Activity*) includes lists of mean values calculated by VPM. When mean values are not available, N/A message is displayed. On the figure bellow are displayed main and axial activity on display with resolution 480 x 800 pixels.

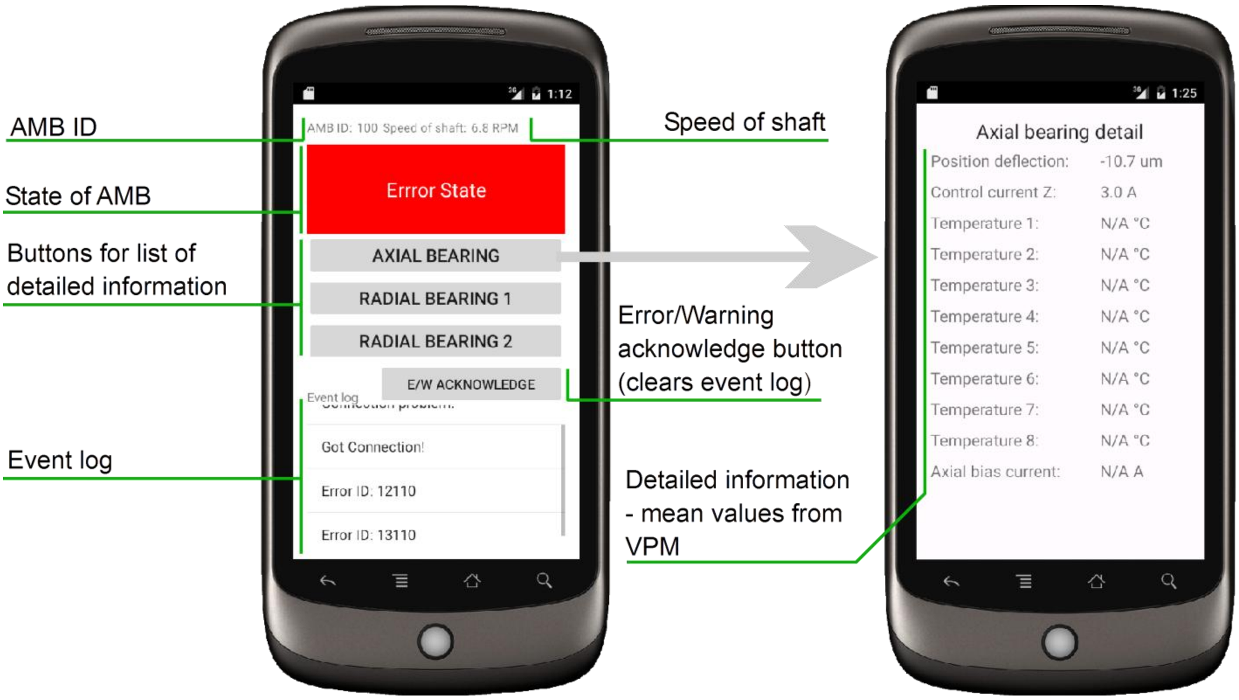


Figure 21 – AMBVisu1 main and axial activity

10.2. Background tasks

Background tasks include communication with maglap++, matching received data to internal variables and creation of message queue for event log. All these background tasks are part of public class *WebService*. Following the ideas of maglap++, data are received in form of matrix, where every column includes different information. First column includes ID of AMB system, second column AMB state ID, third column error IDs, fourth column warning IDs and last column is for mean values. Elements with value equal to -1 are processed as an empty space. Figure below shows example of the matrix.

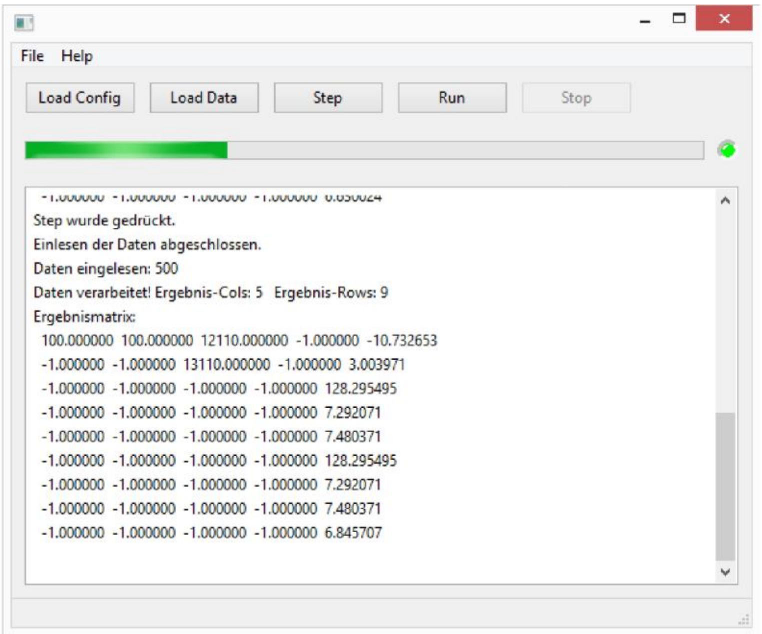


Figure 22 – Server side GUI with transferred matrix

The matrix is received together with *Diag* structure converted to an array with 27 members (header is not transferred). Every member is Boolean value carrying information about specific diagnostic method. Algorithm for reading mean values from the matrix is similar to algorithm described in chapter 9.1. SEM's inputs.

11. Verification

Unfortunately, during writing this master thesis, maglap++ (server side application) was not ready for adding this diagnostic program. Verification of diagnostic results and connection between server and client was done by additional part in diagnostic program written by Dipl.-Inf. (FH) Ivo Noack. This extra part includes basic GUI (figure 22) and simulates functions of maglap++ and will be removed after adding diagnostic program into the maglap++.

11.1. Limit monitoring diagnostics

Limit monitoring is used to detect critical and important values in signals for error, warning and state evaluation. Following tests are performed with real data measured on MFLP, or on simulated signals. MFLP is AMB device with rotor length 2,653 m and weight 1233 kg. This device is located in IPM's testing laboratory in Zittau and its pictures are listed in appendix E. Limit values used for testing of the limit monitoring are selected with help of employees of IPM and their professional knowledge of AMBs. Selected limit values are listed in appendix B (used configuration file). In the following tables are not displayed all values and limit flags due to reduction of size of tables.

11.1.1. Test 1 – Levitating shaft, real data

First verification test is done with real measured data from MFLP. This data set includes eight signals from position sensors of radial bearings. Only position diagnostics for radial bearings can be executed, thus general state of AMB system cannot be determined. Nevertheless, it is possible to monitor program behaviour during shaft levitation. Each signal has sampling rate 25 kHz and one second is recorded. The data are inserted in form of packages with size of 5000 samples. On the following graph are displayed measured signals and in the table is documented detailed program behaviour during signal processing.

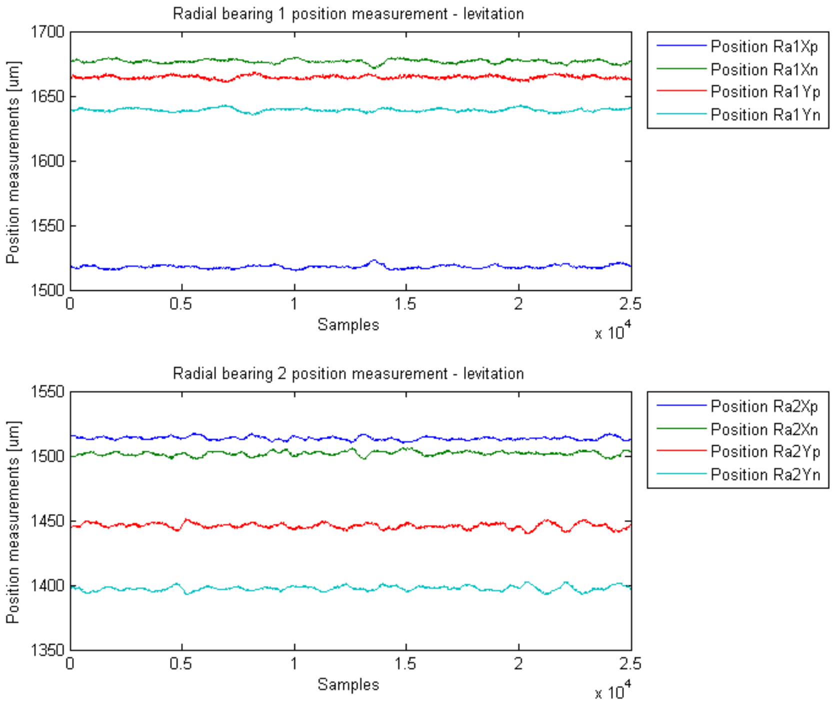


Figure 23 – Test 1, real position signals for levitating shaft

Table 7 – Test 1 processing of position input signals, radial bearing 1

Position diag. - Radial b. 1	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean deflection xy [µm]	80.53	80.756	80.436	80.538	80.01
Mean position x [µm]	79.51	79.762	79.4116	79.51	78.983
Mean position y [µm]	-12.746	-12.52	-12.751	-12.786	-12.702
Effective value xy (max. value) [µm]	1.095	1.631	1.798	1.104	1.358
Effective value x [µm]	1.095	1.175	1.798	1.104	1.268
Effective value y [µm]	1.002	1.631	0.946	1.012	1.358
LF Critical position xy	FALSE	FALSE	FALSE	FALSE	FALSE
LF position in working range	TRUE	TRUE	TRUE	TRUE	TRUE
LF position in back up bearing	FALSE	FALSE	FALSE	FALSE	FALSE
LF xy effective value below limit	TRUE	TRUE	TRUE	TRUE	TRUE
LF deflection gradient too high for cont.	FALSE	FALSE	FALSE	FALSE	FALSE

Table 8 – Test 1 processing of position input signals, radial bearing 2

Position diag. - Radial b. 2	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean deflection xy [μm]	25.563	25.422	24.493	24.607	24.551
Mean position x [μm]	-6.385	-6.157	-5.46	-5.273	-5.950
Mean position y [μm]	-24.723	-24.616	-23.83	-24.006	-23.755
Effective value xy (max. value) [μm]	1.589	1.71	1.736	1.453	2.757
Effective value x [μm]	1.289	1.493	1.581	1.199	1.446
Effective value y [μm]	1.589	1.71	1.655	1.453	2.757
LF Critical position xy	FALSE	FALSE	FALSE	FALSE	FALSE
LF position in working range	TRUE	TRUE	TRUE	TRUE	TRUE
LF position in back up bearing	FALSE	FALSE	FALSE	FALSE	FALSE
LF xy effective value below limit	TRUE	TRUE	TRUE	TRUE	TRUE
LF deflection gradient too high for cont.	FALSE	FALSE	FALSE	FALSE	FALSE

Table 9 – Test 1 results

State evaluation result	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
State ID	300	300	300	300	300
Errors	-	-	-	-	-
Warnings	-	-	-	-	-

Diagnostic program does not find any errors or warnings in given signals. State evaluation module identified state with ID 300 in all data parts. ID of state 300 means that there are no errors or warnings, but the diagnostics program has not enough information to safely recognize some specific state of the system. Interesting values appeared during signals processing in axis X position of the shaft in radial bearing 1. There can be clearly seen relatively big position offset (almost 80 μm) of the shaft from AMB's centre. It can be caused by inaccurate sensor position or by additional offset in the signal.

11.1.2. Test 2 – Shaft falls without rotation, real data

Second test is again done with the real radial position measurements only. Sampling rate is 25 kHz and data are inserted again in data parts with size of 5000 samples for each signal. These signals carries information about shaft fall in first part of data. The minimal AC of signals in following data parts suggests that shaft was not rotating. Tables below graph includes detailed information about signal processing for this test.

Table 10 – Test 2 processing of position input signals, radial bearing 1

Position diag. - Radial b. 1	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean deflection xy [µm]	242.761	330.409	330.477	330.484	330.514
Mean position x [µm]	-84.536	-170.182	-170.274	-170.301	-170.329
Mean position y [µm]	-190.293	-283.198	-283.234	-283.227	-283.245
Effective value xy (max. value) [µm]	126.168	2.096	0.427	0.302	0.28
Effective value x [µm]	116.968	2.096	0.32	0.185	0.177
Effective value y [µm]	126.168	1.696	0.427	0.302	0.28
LF Critical position xy	TRUE	TRUE	TRUE	TRUE	TRUE
LF position in working range	FALSE	FALSE	FALSE	FALSE	FALSE
LF position in back up bearing	FALSE	TRUE	TRUE	TRUE	TRUE
LF xy effective value below limit	FALSE	TRUE	TRUE	TRUE	TRUE
LF deflection gradient too high for cont.	TRUE	FALSE	FALSE	FALSE	FALSE

Table 11 – Test 2 processing of position input signals, radial bearing 1

Position diag. - Radial b. 2	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean deflection xy [µm]	235.974	345.584	345.584	345.636	345.625
Mean position x [µm]	-143.403	-215.42	-215.684	-215.686	-215.699
Mean position y [µm]	-186.096	-270.215	-270.017	-270.081	-270.056
Effective value xy (max. value) [µm]	149.012	2.023	0.368	0.271	0.276
Effective value x [µm]	98.084	1.696	0.299	0.214	0.222
Effective value y [µm]	114.331	2.023	0.368	0.271	0.276
LF Critical position xy	TRUE	TRUE	TRUE	TRUE	TRUE
LF position in working range	FALSE	FALSE	FALSE	FALSE	FALSE
LF position in back up bearing	FALSE	TRUE	TRUE	TRUE	TRUE
LF xy effective value below limit	FALSE	TRUE	TRUE	TRUE	TRUE
LF deflection gradient too high for cont.	TRUE	FALSE	FALSE	FALSE	FALSE

Table 12 – Test 2 results

State evaluation result	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
State ID	100	100	100	100	100
Errors	12110 12130 13110 13130	12110 12130	12110 12130	12110 12130	12110 12130
Warnings	-	-	-	-	-

Detailed analysis shows that even in first data set, critical position was reached in approximately 3300 samples for both radial bearings. Due to the uncontrollable drop of the shaft in first data part, the deflection gradient reached critical values in 732 samples for radial bearing 1 and in 840 samples for radial bearing 2. These events are correctly recognised as error situations. Errors with IDs 12110 and 13110 were present in all data parts. These errors are connected to critical positions. First data part contains extra errors with IDs 12130 and 13130 that are connected to too high position gradient of the shaft. Interesting values are in mean deflection of shaft in both bearings. Deflection values go up to approximately 345 µm even though air gap is only 250 µm. This effect can be caused by deformation of back up bearing under the weight of the shaft, or by additional offset of one or more deflection sensors.

11.1.3. Test 3 – Shaft levitates and rotates, real data

Third test contains position signals for radial bearings during rotation of the levitated shaft. Just by looking at the graph it is clear that there is again deflection or sensor offset in x axis of radial bearing 1. Rotation can be detected by spikes in the signals that are reflected in higher effective values of position during signal processing. Sampling rate and size of data part is same as in previous cases.

Table 13 – Test 3 processing of position input signals, radial bearing 1

Position diag. - Radial b. 1	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean deflection xy [µm]	99.64	100.551	100.059	100.181	100.647
Mean position x [µm]	99.48	100.396	99.894	100.025	100.498
Mean position y [µm]	3.026	3.121	3.249	3.085	2.927
Effective value xy (max. value) [µm]	9.051	5.467	6.042	5.773	5.733
Effective value x [µm]	9.039	5.467	6.028	5.773	5.733
Effective value y [µm]	4.796	4.610	4.749	4.66	4.623
LF Critical position xy	FALSE	FALSE	FALSE	FALSE	FALSE
LF position in working range	TRUE	FALSE	FALSE	FALSE	FALSE
LF position in back up bearing	FALSE	FALSE	FALSE	FALSE	FALSE
LF xy effective value below limit	TRUE	TRUE	TRUE	TRUE	TRUE
LF deflection gradient too high for cont.	TRUE	FALSE	FALSE	FALSE	FALSE

Table 14 – Test 3 processing of position input signals, radial bearing 2

Position diag. - Radial b. 2	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean deflection xy [µm]	18.097	17.997	18.122	17.812	18.467
Mean position x [µm]	6.776	6.212	6.429	6.655	6.688
Mean position y [µm]	-16.259	-16.577	-16.311	-16.179	-16.807
Effective value xy (max. value) [µm]	4.206	3.524	4.799	3.419	4.025
Effective value x [µm]	4.206	3.524	4.177	3.419	4.025
Effective value y [µm]	3.734	3.155	4.799	3.347	3.206
LF Critical position xy	FALSE	FALSE	FALSE	FALSE	FALSE
LF position in working range	TRUE	TRUE	TRUE	TRUE	TRUE
LF position in back up bearing	FALSE	FALSE	FALSE	FALSE	FALSE
LF xy effective value below limit	TRUE	TRUE	TRUE	TRUE	TRUE
LF deflection gradient too high for cont.	TRUE	FALSE	FALSE	FALSE	FALSE

Table 15 – Test 3 results

State evaluation result	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
State ID	100	200	200	200	200
Errors	12130 13130	-	-	-	-
Warnings	-	32110	32110	32110	32110

Surprisingly there were detected errors of too high position gradient (12130, 13130) in both bearings in first data part. By very detailed analysis of input signals were detected few missing samples on the beginning of the signals. These missing samples were interpreted as zero values, thus on the border with real values is detected high position gradient. Limit flag values caused by missing flags are highlighted by blue colour.

Deflection of the shaft or offset of position sensor in X axis of radial bearing 1 caused value of deflection little higher than 100 μm. When the mean deflection is higher than limit value for limit flag of position in normal working range (100 μm), warning 32110 is recognised and state of the AMB system is set to warning state.

Limit values for position effective value below limit should be set to lower value, because despite clear spikes in the signals are these values still set to TRUE value. Limit flags for position effective values below limit does not work correctly in this case, because they should have TRUE value only when the shaft is not rotating. In other situations this problem can lead to incorrect state identification.

11.1.4. Test 4 – Shaft falls in radial bearing 2, real data

Following test used position data from radial bearings when shaft in radial bearing 2 fell down. Shaft remained levitating in radial bearing 1. AC of signals suggest that shaft was not rotating during the drop. Sampling rate and size of data part is again same as in previous cases.

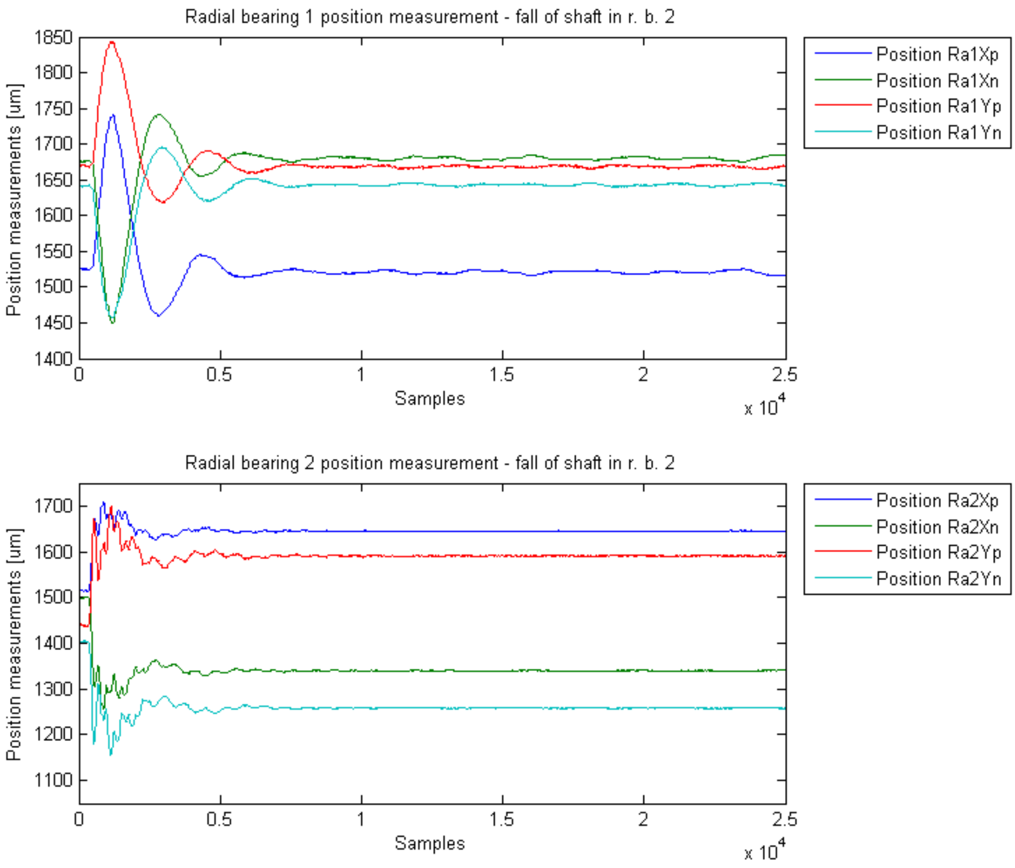


Figure 24 – Test 4, real position signals for fall of the shaft in radial bearing 2

Table 16 – Test 4 processing of position input signals, radial bearing 1

Position diag. - Radial b. 1	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean deflection xy [µm]	112.309	81.4794	80.228	80.973	80.497
Mean position x [µm]	44.065	80.379	79.176	79.905	79.502
Mean position y [µm]	-44.043	-12.424	-12.861	-13.036	-12.515
Effective value xy (max. value) [µm]	80.537	4.485	1.966	1.957	2.415
Effective value x [µm]	80.537	3.412	1.966	1.957	2.415
Effective value y [µm]	68.715	4.485	1.443	1.364	1.588
LF critical position xy	TRUE	FALSE	FALSE	FALSE	FALSE
LF position in working range	FALSE	TRUE	TRUE	TRUE	TRUE
LF position in back up bearing	FALSE	FALSE	FALSE	FALSE	FALSE
LF xy effective value below limit	FALSE	TRUE	TRUE	TRUE	TRUE
LF deflection gradient too high for cont.	TRUE	FALSE	FALSE	FALSE	FALSE

Table 17 – Test 4 processing of position input signals, radial bearing 2

Position diag. - Radial b. 2	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean deflection xy [µm]	219.562	225.23	225.592	225.628	225.621
Mean position x [µm]	-147.208	-152.358	-152.618	-152.42	-152.576
Mean position y [µm]	-162.182	-165.866	-166.13	-166.36	-166.207
Effective value xy (max. value) [µm]	67.619	2.172	0.731	0.661	0.683
Effective value x [µm]	46.952	1.466	0.55	0.510	0.623
Effective value y [µm]	51.011	2.172	0.731	0.661	0.683
LF critical position xy	TRUE	TRUE	TRUE	TRUE	TRUE
LF position in working range	FALSE	FALSE	FALSE	FALSE	FALSE
LF position in back up bearing	FALSE	FALSE	FALSE	FALSE	FALSE
LF xy effective value below limit	FALSE	TRUE	TRUE	TRUE	TRUE
LF deflection gradient too high for cont.	TRUE	FALSE	FALSE	FALSE	FALSE

Table 18 – Test 4 results

State evaluation result	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
State ID	100	100	100	100	100
Errors	12110 12130 13110 13130	13110	13110	13110	13110
Warnings	-	-	-	-	-

Result of first data part processing are the same errors as in case of test 2. Critical position is detected in 482 samples for radial bearing 1 and in 4463 samples in radial bearing 2. Position gradient was too high in 230 cases for radial bearing 1 and in 778 cases for radial bearing 2. Position in radial bearing 1 is back in normal working range in the second data part (0,2s to 0,4s). Error 13110 correctly remains for last four data parts, because shaft is touching back up bearing in only one radial bearing. Effective values of data parts give us clear information about stabilizing of shaft position.

11.1.5. Test 5 – Shaft falls during rotation, real data

Test 5 contains complete position, control current and rotation data for event of shaft fall. In the first part of the test were all measurement signal types tested separetly and in the second part of the test all data were processed at the same time. The fall of the shaft is recorded in second data part, approximatelly in 0,25 s. Sampling rate and size of data part are again same as in previous cases.

Position diagnostics testing

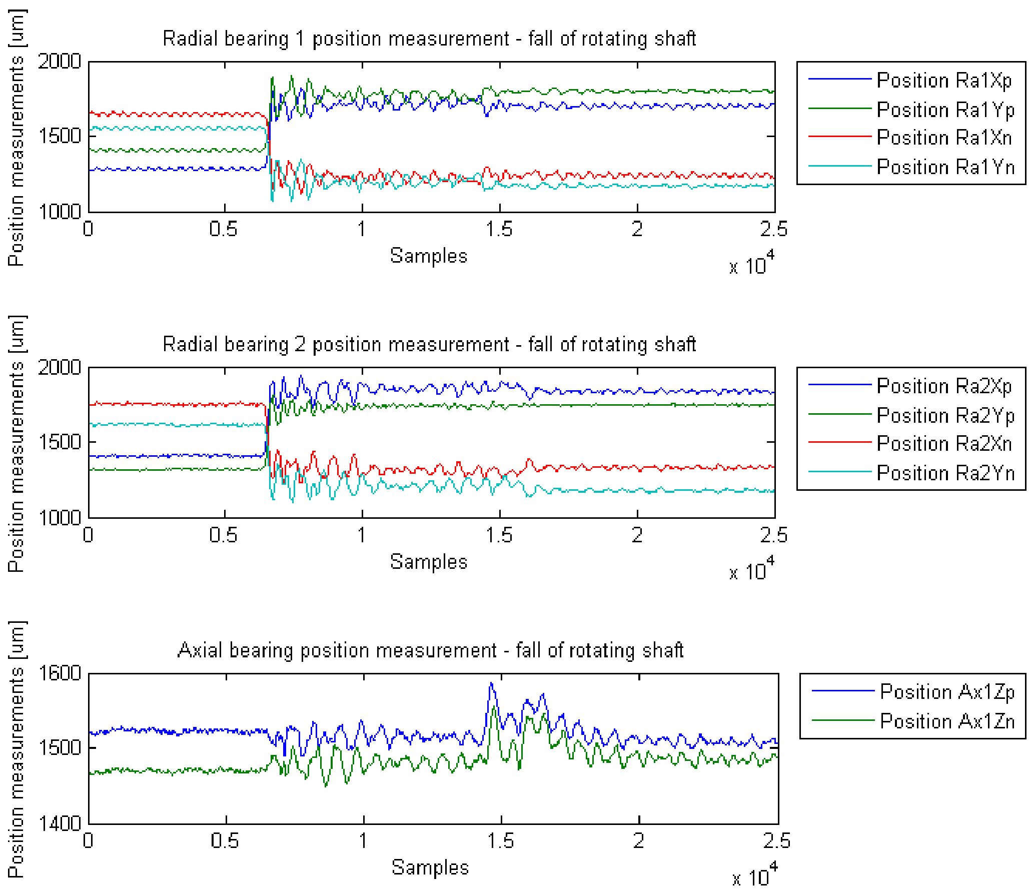


Figure 25 – Test 5, real position signals for fall of the rotating shaft

Table 19 – Test 5 processing of position input signals, axial bearing

Position diag. – Axial bearing	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean position z [µm]	-26.342	-20.112	-17.2294	-13.534	-11.67
Effective value z [µm]	1.99	7.462	5.822	4.563	1.728
LF critical position z	FALSE	FALSE	FALSE	FALSE	FALSE
LF position in working range	TRUE	TRUE	TRUE	TRUE	TRUE
LF position in back up bearing	FALSE	FALSE	FALSE	FALSE	FALSE
LF Z effective value below limit	TRUE	TRUE	TRUE	TRUE	TRUE
LF deflection gradient too high for cont.	TRUE	TRUE	TRUE	TRUE	TRUE

Table 20 – Test 5 processing of position input signals, radial bearing 1

Position diag. - Radial b. 1	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean deflection xy [µm]	195.908	311.525	378.105	390.03	389.758
Mean position x [µm]	182.199	-101.254	-243.994	-230.861	-231.007
Mean position y [µm]	71.672	-168.947	-286.362	-313.945	-313.748
Effective value xy (max. value) [µm]	14.121	195.871	28.136	14.852	24.755
Effective value x [µm]	13.359	195.871	27.3726	14.852	17.59
Effective value y [µm]	8.206	169.545	28.136	10.062	20.311
LF critical position xy	TRUE	TRUE	TRUE	TRUE	TRUE
LF position in working range	FALSE	FALSE	FALSE	FALSE	FALSE
LF position in back up bearing	FALSE	TRUE	TRUE	TRUE	TRUE
LF xy effective value below limit	TRUE	FALSE	FALSE	TRUE	FALSE
LF deflection gradient too high for cont.	TRUE	TRUE	TRUE	TRUE	TRUE

Table 21 – Test 5 processing of position input signals, radial bearing 2

Position diag. - Radial b. 2	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean deflection xy [µm]	227.255	314.114	379.664	381.686	380.177
Mean position x [µm]	171.404	-121.372	-271.503	-257.58	-252.153
Mean position y [µm]	149.165	-127.935	-264.184	-280.31	-284.399
Effective value xy (max. value) [µm]	15.345	199.549	21.922	21.569	24.191
Effective value x [µm]	11.912	199.549	21.922	21.569	18.241
Effective value y [µm]	10.435	186.771	17.432	14.775	17.98
LF critical position xy	TRUE	TRUE	TRUE	TRUE	TRUE
LF position in working range	FALSE	FALSE	FALSE	FALSE	FALSE
LF position in back up bearing	FALSE	TRUE	TRUE	TRUE	TRUE
LF xy effective value below limit	FALSE	FALSE	FALSE	FALSE	FALSE
LF deflection gradient too high for cont.	TRUE	TRUE	TRUE	TRUE	TRUE

Table 22 – Test 5 results for position signals processing

State evaluation result	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
State ID	100	100	100	100	100
Errors	11130 12110 12130 13110 13130	11130 12110 12130 13110 13130	11130 12110 12130 13110 13130	11130 12110 12130 13110 13130	11130 12110 12130 13110 13130
Warnings	-	-	-	-	-

In the first data part are detected "position gradient too high errors" in every bearing – 15 cases for axial bearing, 100 cases for radial bearing 1 and 86 cases for radial bearing 2. Critical positions are detected in both radial bearings – 2056 samples in radial bearing 1 and 4981 samples in radial bearing 2.

In the second data part amount of detection of "position gradient too high errors" is rising rapidly to 30 cases for axial bearing, 2642 cases for radial bearing 1 and 2909 cases for radial bearing 2. Amount of detection of critical position is very high for both radial bearings – 3942 for radial bearing 1 and 4783 for radial bearing 2.

Rest of testing data shows large amount of detection of critical positions in radial bearings and decreasing amount of critical gradient of position together with decreasing effective values of positions in all bearings. Every data part is correctly detected as an error state, although limit flags for effective value of position should have again lower limit values.

One of measured position signal from axial bearing is probably inverted – it is highly improbable that size of the shaft is changing. Unfortunately, diagnostic program is not able to detect this failure.

Control current testing

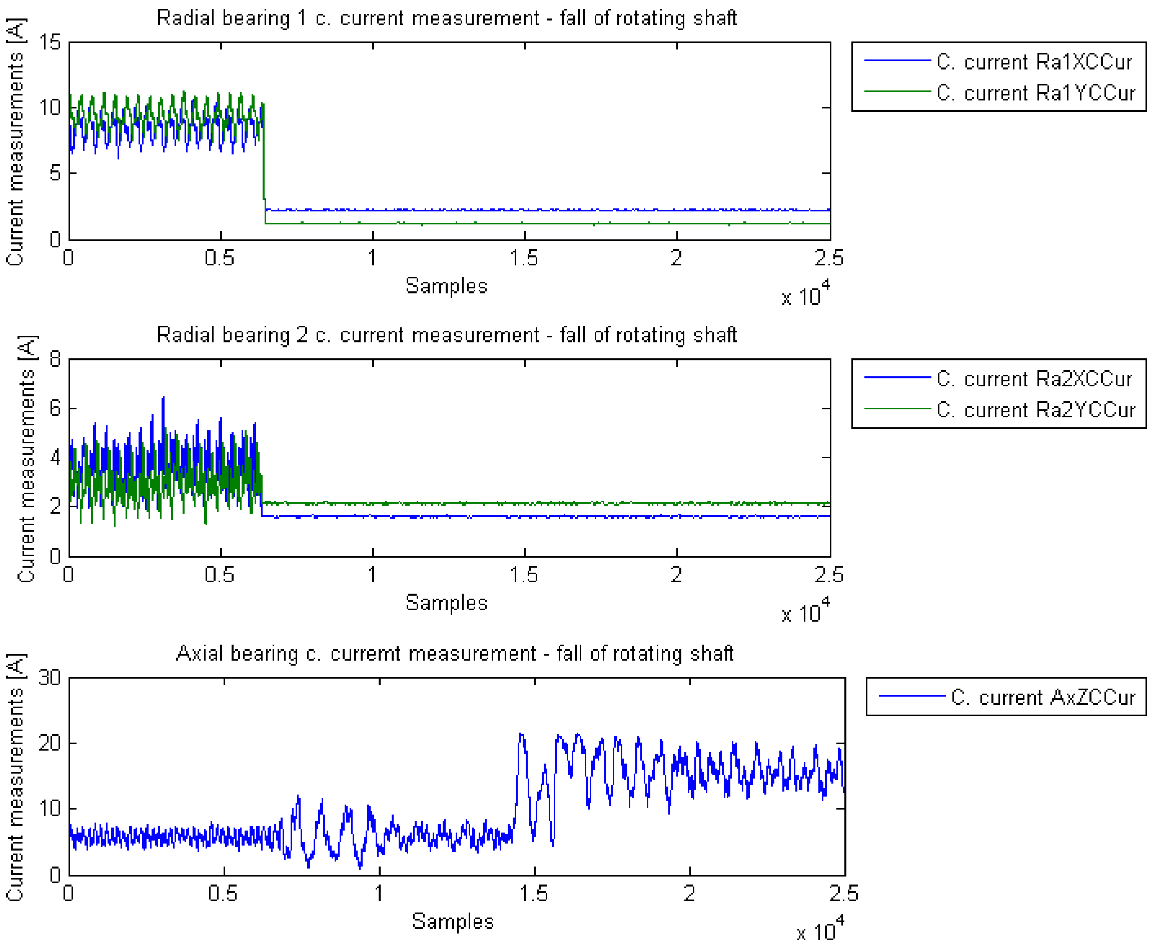


Figure 26 – Test 5, real control current signals for fall of the rotating shaft

Table 23 – Test 5 processing of control current input signals, axial bearing

C. current diag. – Axial bearing	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean value c. current z [A]	5.739	5.787	6.873	16.0123	15.491
Effective value c. current z [A]	0.919	2.305	3.674	3.735	2.169
LF Mean value below minimal value limit z	FALSE	FALSE	FALSE	FALSE	FALSE
z effective value below limit	FALSE	FALSE	FALSE	FALSE	FALSE

Table 24 – Test 5 processing of control current input signals, radial bearing 1

C. current diag. – Radial bearing 1	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean value of c. current x [A]	8.426	4.026	2.212	2.205	2.202
Mean value of c. current y [A]	9.244	3.516	1.189	1.186	1.183
Effective value of c. current x [A]	1.046	2.88	0.027	0.03	0.139
Effective value of c. current y [A]	1.049	3.667	0.027	0.026	0.078
LF Mean value below minimal value limit x	FALSE	FALSE	FALSE	FALSE	FALSE
LF Mean value below minimal value limit y	FALSE	FALSE	FALSE	FALSE	FALSE
x effective value below limit	FALSE	FALSE	TRUE	TRUE	TRUE
y effective value below limit	FALSE	FALSE	TRUE	TRUE	TRUE

Table 25 – Test 5 processing of control current input signals, radial bearing 2

C. current diag. – Radial bearing 2	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean value of c. current x [A]	3.573	2.128	1.61	1.609	1.604
Mean value of c. current y [A]	2.978	2.425	2.14	2.142	2.136
Effective value of c. current x [A]	0.85	0.95	0.017	0.023	0.101
Effective value of c. current y [A]	0.789	0.607	0.022	0.026	0.134
LF Mean value below minimal value limit x	FALSE	FALSE	FALSE	FALSE	FALSE
LF Mean value below minimal value limit y	FALSE	FALSE	FALSE	FALSE	FALSE
x effective value below limit	FALSE	FALSE	TRUE	TRUE	TRUE
y effective value below limit	FALSE	FALSE	TRUE	TRUE	TRUE

Table 26 – Test 5 results for control current signals processing

State evaluation result	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
State ID	300	300	300	300	300
Errors	-	-	-	-	-
Warnings	-	-	-	-	-

In the beginning of the data are shown oscillating control currents for radial bearings. These control currents are turned off during the processing of second data part causing fall of the shaft. Control current of axial bearing starts to highly oscillate when the controller is trying to compensate shaking of the fallen shaft.

State ID is identified correctly in all data parts, although limit flags for mean control currents below minimal value limit were expected to be TRUE after turning control currents off. This wrong identification of limit flags is caused by not very precise control current measurement sensors, that are adding large offset into the signals. It is not recommended to change limit values for these limit flags.

Rotation testing

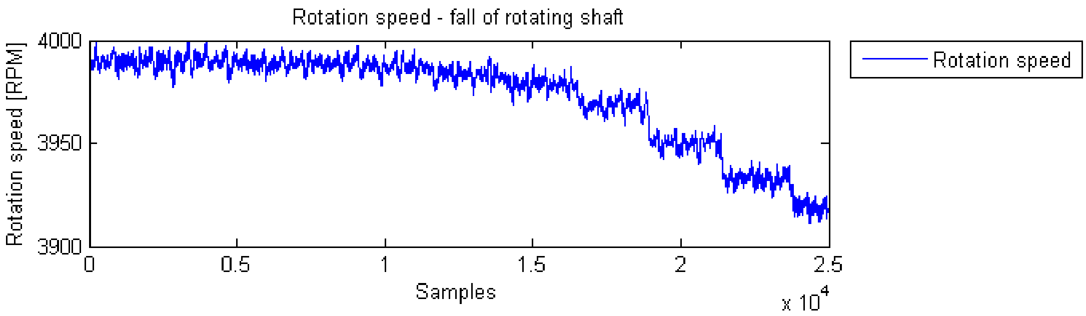


Figure 27 – Test 5, real rotation signal for fall of the shaft

Table 27 – Test 5 processing of rotation input signal

Rotation diagnostics	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean rotation speed [RPM]	3974.46	3988.42	3983.48	3967.78	3919.19
Acceleration [ΔRPM/s]	152.607	-2.93	-22.455	-70.341	-233.42
LF Rotation is too high	FALSE	FALSE	FALSE	FALSE	FALSE
LF Rotation is too low	FALSE	FALSE	FALSE	FALSE	FALSE
LF Zero or minimal rotation	FALSE	FALSE	FALSE	FALSE	FALSE
LF Shaft is accelerating	TRUE	FALSE	FALSE	FALSE	FALSE
LF Shaft is decelerating	FALSE	FALSE	TRUE	TRUE	TRUE

Table 28 – Test 5 results for rotation signal processing

State evaluation result	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
State ID	300	300	300	300	300
Errors	-	-	-	-	-
Warnings	-	-	-	-	-

Rotation data show us clear deceleration of the shaft after falling down. Acceleration and deceleration values in first and last data parts can be enlarged by missing a few lines of data on the beginning and the end of signal data. Missing data are again automatically replaced by zero values. Nevertheless, deceleration of the shaft and state ID were correctly identified.

All measured signals simultaneously

Table 29 – Test 5 results for all measured signals simultaneously

State evaluation result	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
State ID	100	100	100	100	100
Errors	11130 12110 12130 13110 13130	11130 12110 12130 13110 13130	11130 12110 12130 13110 13130	11130 12110 12130 13110 13130	11130 12110 12130 13110 13130
Warnings	-	-	-	-	-

After processing all measured data together, errors from position signals are detected and the state of shaft is correctly recognised as an error state with ID 100.

11.1.6. Test 6 – Test of temperature and bias current, simulation

Data sets in test 5 did not include any information about temperatures and bias currents. Due to this reason, temperatures and bias currents are tested separately with simulated values.

Diagnostic program is able to diagnose eight temperature sensors per magnetic bearing. Three different temperature errors were simulated. First error signal is linearly rising temperature up to critical values. Second error signal includes data about high offset of sensor or sensor over range. Last error signal includes high spikes, that should be detected as sensor error. These three error signals are inserted to temperature sensors 6, 7 and 8. Signals for sensors 1-5 are shown on the second figure.

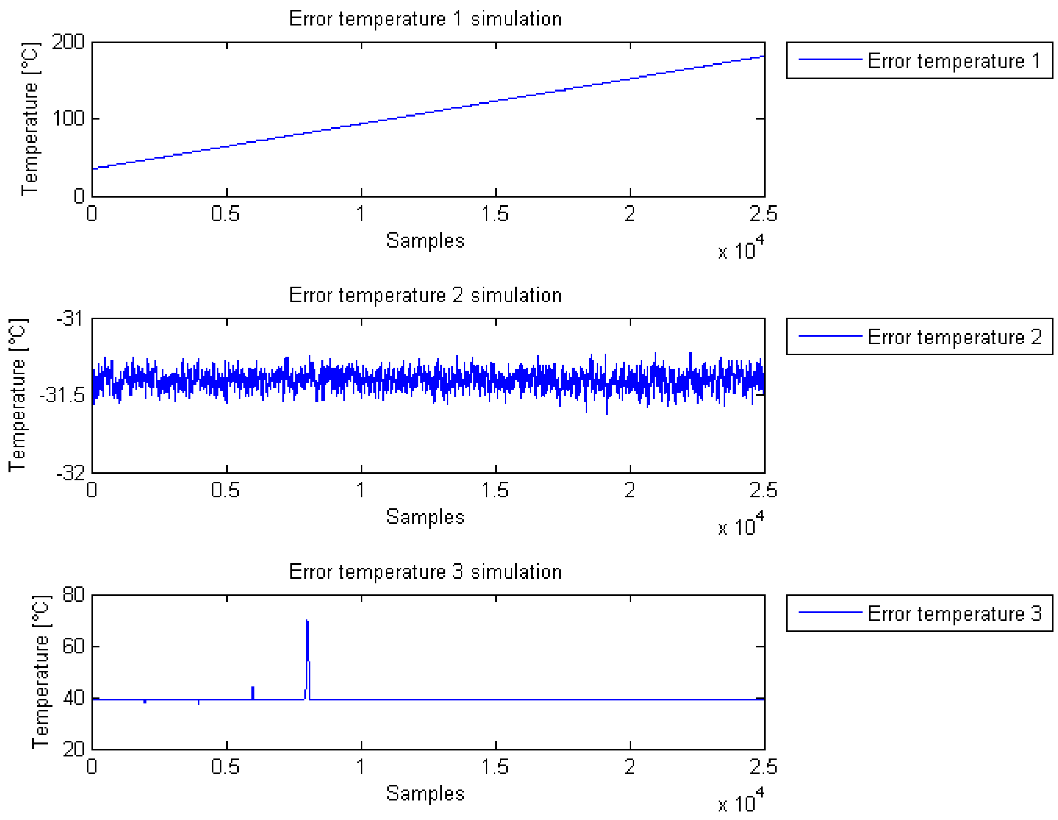


Figure 28 – Test 6, simulated temperature error signals

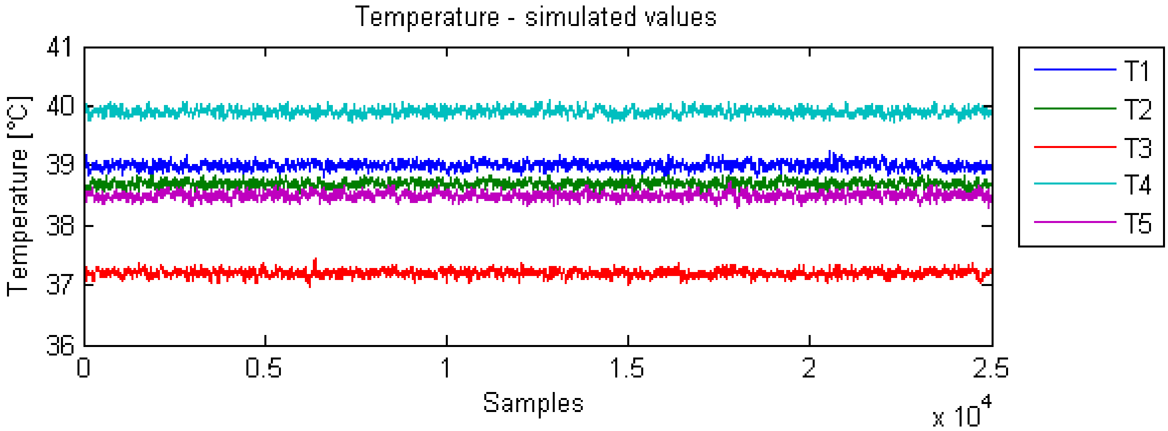


Figure 29 - Test 6, simulated temperature common signals

Table 30 – Test 6 processing of temperature input signals

Temperature diagnostics - simulated	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean value temperature 1 [°C]	38.847	39.01	39.008	39.004	38.857
Mean value temperature 2 [°C]	38.549	38.697	38.697	38.708	38.551
Mean value temperature 3 [°C]	37.067	37.201	37.209	37.195	37.065
Mean value temperature 4 [°C]	39.756	39.903	39.913	39.907	39.744
Mean value temperature 5 [°C]	38.349	38.513	38.496	38.496	38.259
Mean value temperature 6 [°C]	49.079	78.395	107.596	136.802	165.323
Mean value temperature 7 [°C]	-31.2862	-31.396	-31.4	-31.41	-31.285
Mean value temperature 8 [°C]	38.825	39.676	39.008	39.004	38.857
LF Critical temperature sensor 1	FALSE	FALSE	FALSE	FALSE	FALSE
LF Critical temperature sensor 2	FALSE	FALSE	FALSE	FALSE	FALSE
LF Critical temperature sensor 3	FALSE	FALSE	FALSE	FALSE	FALSE
LF Critical temperature sensor 4	FALSE	FALSE	FALSE	FALSE	FALSE
LF Critical temperature sensor 5	FALSE	FALSE	FALSE	FALSE	FALSE
LF Critical temperature sensor 6	FALSE	FALSE	FALSE	TRUE	TRUE
LF Critical temperature sensor 7	FALSE	FALSE	FALSE	FALSE	FALSE
LF Critical temperature sensor 8	FALSE	FALSE	FALSE	FALSE	FALSE
LF Sensor error 1	TRUE	FALSE	FALSE	FALSE	TRUE
LF Sensor error 2	TRUE	FALSE	FALSE	FALSE	TRUE
LF Sensor error 3	TRUE	FALSE	FALSE	FALSE	TRUE
LF Sensor error 4	TRUE	FALSE	FALSE	FALSE	TRUE
LF Sensor error 5	TRUE	FALSE	FALSE	FALSE	TRUE
LF Sensor error 6	TRUE	FALSE	FALSE	FALSE	TRUE
LF Sensor error 7	TRUE	TRUE	TRUE	TRUE	TRUE
LF Sensor error 8	TRUE	TRUE	FALSE	FALSE	TRUE

Table 31 – Test 6 results for temperature signals processing

State ID	100	100	100	100	100
Errors	11321 11322 11323 11324 11325 11326 11327 11328	11327 11328	11327	11316 11327	11327 11321 11322 11323 11324 11325 11326 11327 11328
Warnings	-	-	-	-	-

Results show us sensor errors (11321-11328) in every channel at the beginning and end of the testing data. These errors are again caused by missing values in given data. Critical temperature is correctly identified in last two data sets of sensor 6. Every data part of sensor 7 is correctly identified as sensor error. First two data sets of sensor 8 signal are also correctly identified as sensor error due to spikes in the signal (spikes in first data part are very thin and cannot be seen from the graph above). Limit flags that are set to TRUE value incorrectly by missing data are highlighted by blue colour.

On the following graph is displayed simulated value of bias current. Bias current is turned off in the same time as control current in test 5.

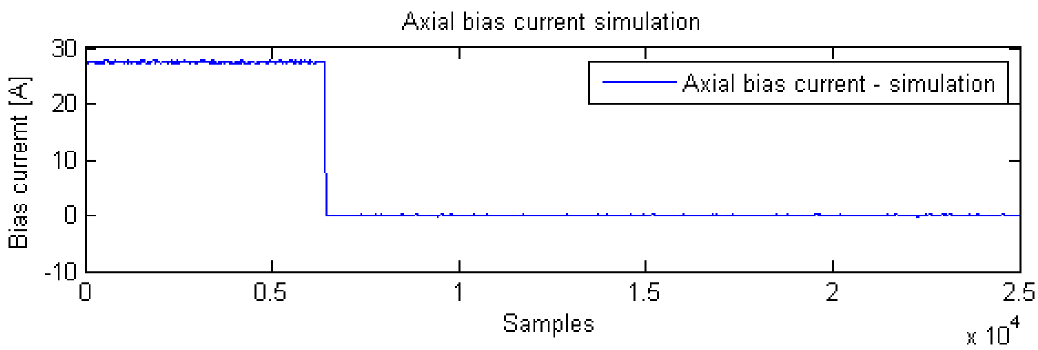


Figure 30 – Test 6, simulated bias current signal

Table 32 – Test 6 processing of bias current signal

Axial bias current diag. - simulated	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean bias current [A]	27.374	7.976	0.044	0.0518	0.049
LF Maximal mean current	FALSE	FALSE	FALSE	FALSE	FALSE
LF Critical current	FALSE	FALSE	FALSE	FALSE	FALSE
LF Minimal mean bias current	FALSE	FALSE	TRUE	TRUE	TRUE

Table 33 – Test 6 results for bias current signal processing

State evaluation result	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
State ID	300	300	300	300	300
Errors					
Warnings	-	-	-	-	-

Diagnostic program correctly identified bias current switching off. Limit flags for minimal mean bias current can be used as an alternative to limit flags for minimal mean control current in state identification.

11.1.7. Test 7 – Test of correct state evaluation, simulation

Unfortunately, any previous data sets did not included signals for testing states that are not resulting as error, warning or not enough data. Following simulated signals are used for simulation of shaft lifting, normal operation, accelerating, decelerating and shaft fall. Please, note that the simulation data are not created by exact mathematical model of the AMB system. Important features for testing are changes in mean and effective values of signals, not precise shapes of signals. Data packages includes 500 values and sampling rate is 1 kHz.

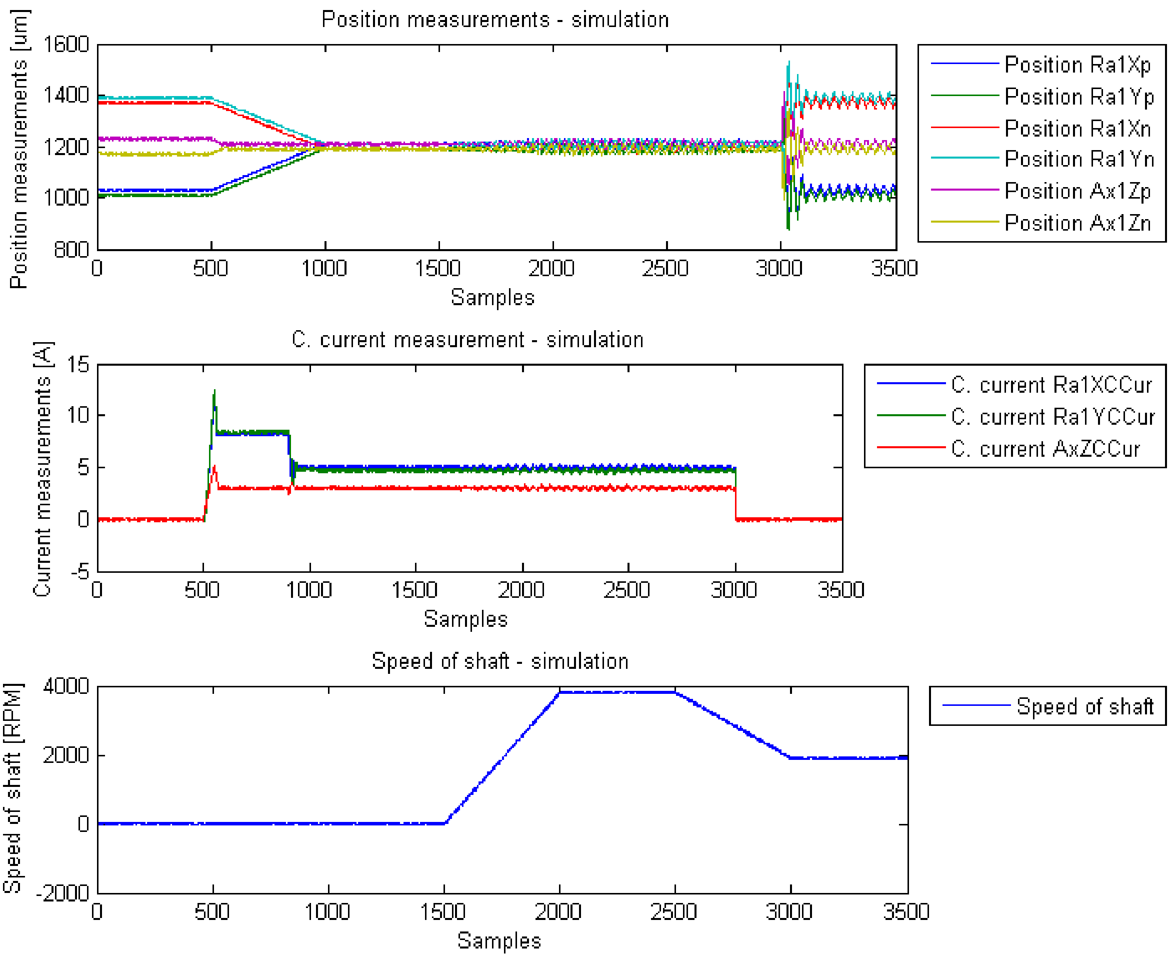


Figure 31 – Test 7, simulated signals for state evaluation

Table 34 – Test 7 processing of input signals

State evaluation testing	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5	Data part 6	Data part 7
Mean position axial z [µm]	-29.866	-10.733	-9.946	-9.746	-10.368	-9.625	-12.235
Eff. value position axial z [µm]	1.906	3.518	1.879	6.796	11.761	8.898	36.4
Mean c. current axial z [A]	0.001	3.004	2.994	2.999	3.006	2.994	0.01
Eff. value c. current axial z [A]	0.082	0.546	0.084	0.107	0.1407	0.183	0.08
Mean position radial xy [µm]	255.099	128.295	14.312	16.7	21.021	18.45	249.672
Eff. value position radial xy [µm]	2.24	72.075	1.56	6.798	11.714	8.877	51.84
Mean c. current radial x [A]	0	7.292	4.994	4.999	5.006	4.99	0.01
Mean c. current radial y [A]	0	7.48	4.701	4.699	4.706	4.69	0.01
Eff. value c. current radial x [A]	0.082	2.017	0.084	0.107	0.141	0.258	0.08
Eff. value c. current radial y [A]	0.082	2.135	0.088	0.107	0.141	0.246	0.08
Mean rotation speed [RPM]	6.63	6.846	6.959	1895.95	3800.86	2845.97	1901.61
Acceleration [ΔRPM/s]	0.982	-0.669	-0.169	3801.09	6.145	-1903.4	4.198
All position eff. values below limit	TRUE	-	TRUE	TRUE	TRUE	TRUE	-
All c. cur. eff. values below limit	TRUE	-	TRUE	TRUE	TRUE	TRUE	-
All mean c. currents below limit	TRUE	-	FALSE	FALSE	FALSE	FALSE	-
Shaft in working range in all AMBs	FALSE	-	TRUE	TRUE	TRUE	TRUE	-
LF Rotation is too low	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE
LF Zero or minimal rotation	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE
LF Shaft is accelerating	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE
LF Shaft is decelerating	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE

Table 35 – Test 7 results

State result	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5	Data part 6	Data part 7
State ID	401	100	402	404	403	405	100
Errors	-	12110 13110					11110 11130 12110 12130 13110 13130
Warnings	-	-	-	-	-	-	34110

In first part is state of AMB system detected as shaft lies on backup bearings (ID 401). This state is identified correctly because shaft is not rotating (mean rotation speed value 6.63 RPM is caused by noise in signal) and lies in radial backup bearings (horizontal shaft) with turned off control currents. During the second part is shaft getting into normal operation position. Unfortunately the diagnostic program recognise this phase as an error state, because shaft has critical position and control currents are switched on. One possible way how to remove this failure is to add commands from control panel into error evaluation part of diagnostic program. Third data part is correctly recognised as stand by state (ID 402), because shaft is levitating in normal working range without rotation. After this part shaft starts to spin, effective values of control currents and position are rising and state is indentified as acceleration (ID 404). Low speed warning is correctly suppressed. In the middle of testing data is identified normal operation state (ID 403) followed by deceleration state (ID 405), where low speed warning is also correctly suppressed. Last part of the data simulates switching off of the control currents. Program correctly identified critical positions, critical position gradients and warning of low rotation speed. This state is similar to test 5.

11.2. Fuzzy logic monitoring verification

Fuzzy logic monitoring is used for detection of errors in control loop settings. This type of monitoring is used separately for each axis. In every axis are used same functions, thus it is tested only one axis – z axis of axial bearing. Unfortunately there are not available any real measured situations of diagnosed errors or fuzzy sets based on professional knowledge of given AMB system. Verification is done by expected changes in signals and by approximated fuzzy sets. Used fuzzy sets and other important values are listed in appendix B (used configuration file).

11.2.1. Test 8 – Position sensor diagnostics, simulation

For position sensor diagnostics is necessary to calculate mean and effective values of force, W ratio, mean value of control current and mean value of voltage. Simulated signals with changing properties are displayed below. For changing of force amplitude is used shift of control current offset and constant deflection of the shaft. Force value rises with rising of control current offset. Bias current has also nearly constant value. Changes in effective value of force are done by changing AC component of control current and position. It is important to not change W ratio significantly by changes in effective values.

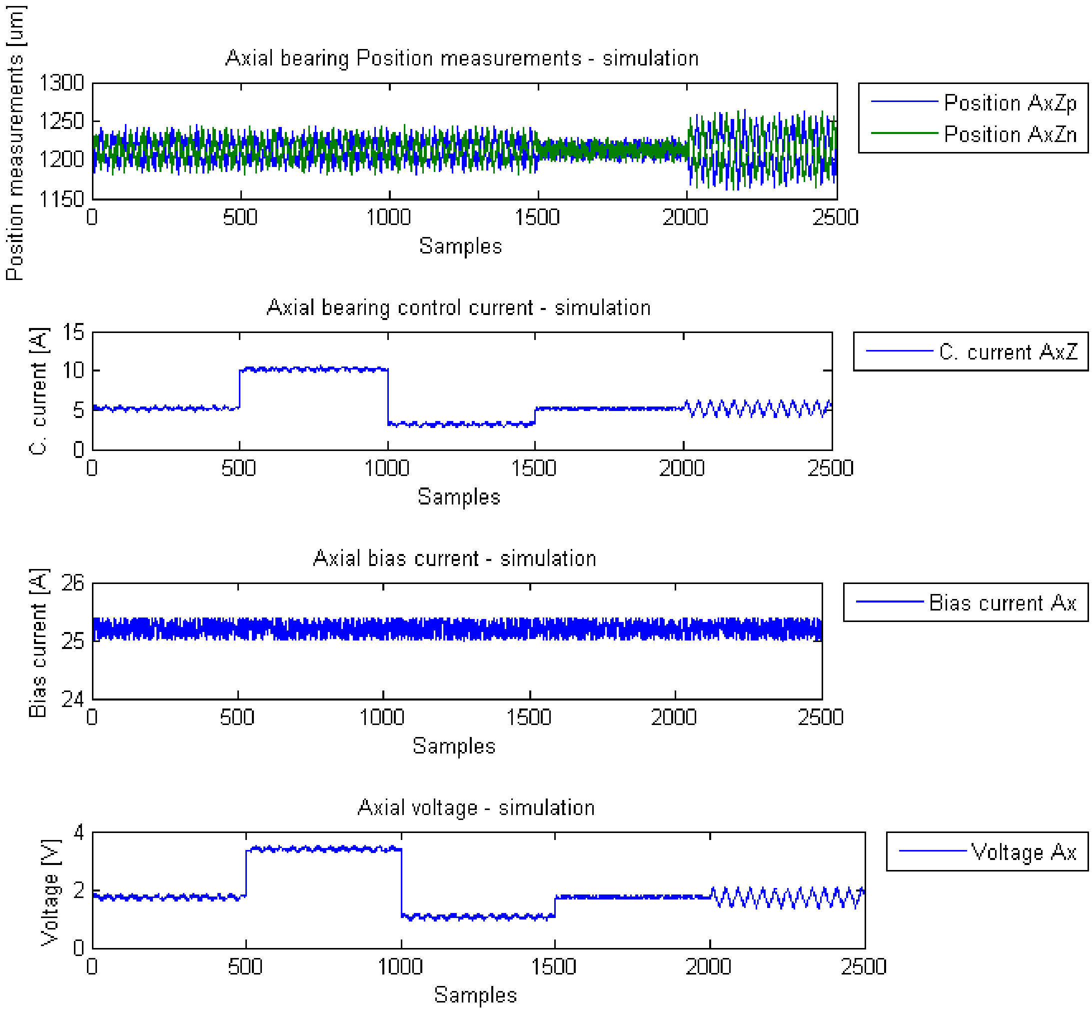


Figure 32 – Test 8, simulated signals

Table 36 – Test 8 processing of signals

Sensor diagnostics - simulation	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Position mean value axial z [µm]	0.53	-0.303	0.486	-0.04	1.069
Position effective value axial z [µm]	12.719	12.717	12.629	5.868	23.37
Mean c. current axial [A]	5.212	10.175	3.207	5.199	5.219
Axial c. current effective value [A]	0.273	0.35	0.185	0.117	0.593
Mean b. current axial [A]	25.198	25.201	25.2	25.204	25.206
Mean force [N]	4824.93	9414.53	2969.85	4811.92	4836.42
Effective value of force [N]	272.815	341.858	198.939	97.311	646.638
W ratio	0.021	0.027	0.0146	0.02	0.025
Mean voltage [V]	1.737	3.392	1.069	1.733	1.74
Mean force membership value - small	0	0	1	0	0
Mean force membership value - normal	0.938	0	0	0.97	0.909
Mean force membership value - big	0.062	1	0	0.03	0.091
W ratio membership value - small	0	0	0.537	0.007	0
W ratio membership value - normal	1	0.65	0.463	0.993	0.864
W ratio membership value - big	0	0.35	0	0	0.136
Mean c. current membership value - small	0	0	0.529	0	0
Mean c. current membership value - normal	1	0	0.471	1	1
Mean c. current membership value - big	0	1	0	0	0
Effective value force membership v. - small	0	0	0.638	1	0
Effective value force membership v. - normal	1	1	0.362	0	0
Effective value force membership v. - big	0	0	0	0	1
Mean voltage - small	0	0	0.862	0	0
Mean voltage - normal	1	0	0.138	1	1
Mean voltage - big	0	1	0	0	0
Fuzzy sum for ES1P	0.062	1	0	0.03	0.091
Fuzzy sum for ES1N	0	0	1	0	0
Fuzzy sum for ES2P	0	0	0.139	0.993	0
Fuzzy sum for ES2N	0	0	0	0	0.864
Error ES1P	FALSE	TRUE	FALSE	FALSE	FALSE
Error ES1N	FALSE	FALSE	TRUE	FALSE	FALSE
Error ES2P	FALSE	FALSE	FALSE	TRUE	FALSE
Error ES1N	FALSE	FALSE	FALSE	FALSE	TRUE

During processing first dataset are all “normal” membership values set to 1. Only membership value for big force is starting to rise. But this deviation is small and cannot influence error identification process. In the second part, membership value of big force is calculated as 1 and causes ES1P error to be set on TRUE value. Third part of testing is inverse to the second part and membership value of small force is equal to 1 – ES2P is set to TRUE. During these two data parts are interesting changes in W ratio. In last two data sets W ratio is still "sufficiently normal" and changing of effective value of force causes recognition of ES2P and ES2N errors.

11.2.2. Test 9 – Controller diagnostics, simulation

For controller diagnostics are needed only three signals. First signal is voltage and the rest of signals are position signals from opposite deflection sensors. Position of the shaft is different in every data part. Effective value of position is rising with time unlike effective value of voltage, that is nearly constant. This changes in position effective value causes rising of R ratio.

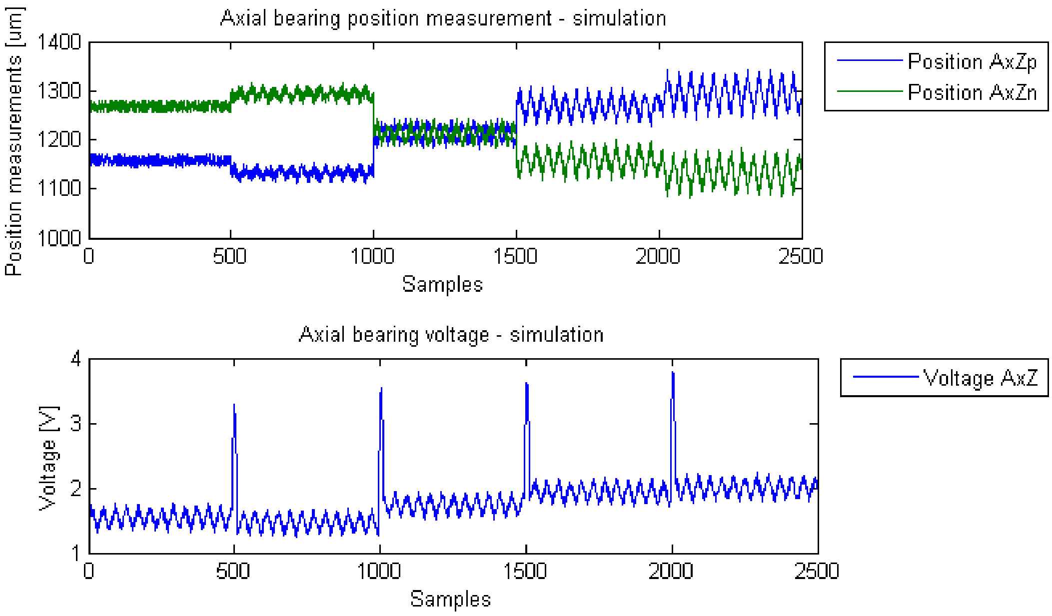


Figure 33 – Test 9, simulated signals

Table 37 – Test 9 processing of signals

Controller diagnostics - simulation	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean position z [µm]	55.303	79.861	0.171	-55.667	-79.324
Position effective value z [µm]	5.102	8.357	12.834	18.169	23.574
Voltage effective value z [V]	0.218	0.256	0.271	0.26	0.234
R ratio	23.392	32.65	47.404	69.894	100.552
Membership value – R small	1	0.823	0	0	0
Membership value – R normal	0	0.177	1	0.007	0
Membership value – R big	0	0	0	0.993	1
Membership value – mean position small	0	0	0	0.113	0.586
Membership value – mean position normal	0.894	0.403	1	0.887	0.414
Membership value – mean position big	0.106	0.597	0	0	0
Error EC1P	TRUE	TRUE	FALSE	FALSE	FALSE
Error EC1N	FALSE	FALSE	FALSE	TRUE	TRUE
Error EC2P	FALSE	FALSE	FALSE	FALSE	TRUE
Error EC2N	FALSE	TRUE	FALSE	FALSE	FALSE

In the first data set effective value of position is small in comparison to effective value of voltage. This leads to small R ratio and EC1P error is set to TRUE. In the second part, position deflection is large and R ratio keeps small so errors EC1P and EC2N are identified correctly. In the third part has every value "normal" membership and all errors are set to FALSE. In the third and fourth data part is R ratio large so EC1N is set to TRUE. Position is relatively well below normal working point in fourth data set and EC2N is set to TRUE.

11.2.3. Test 10 – Control signal diagnostics

Control signal diagnostics requires signals from position, control current, bias current and voltage sensors. If control current, bias current and mean value of force are "sufficiently normal" than it is possible to cause ECS1P and ECS1N just by changing offset of voltage signal. Errors ECS2P and ECS2N can be caused by changing ratio of effective values of control current and effective value of voltage signal. Normal membership values of bias and control current are constantly equal to 1. Due to reduction of table size, membership values for the currents are not included.

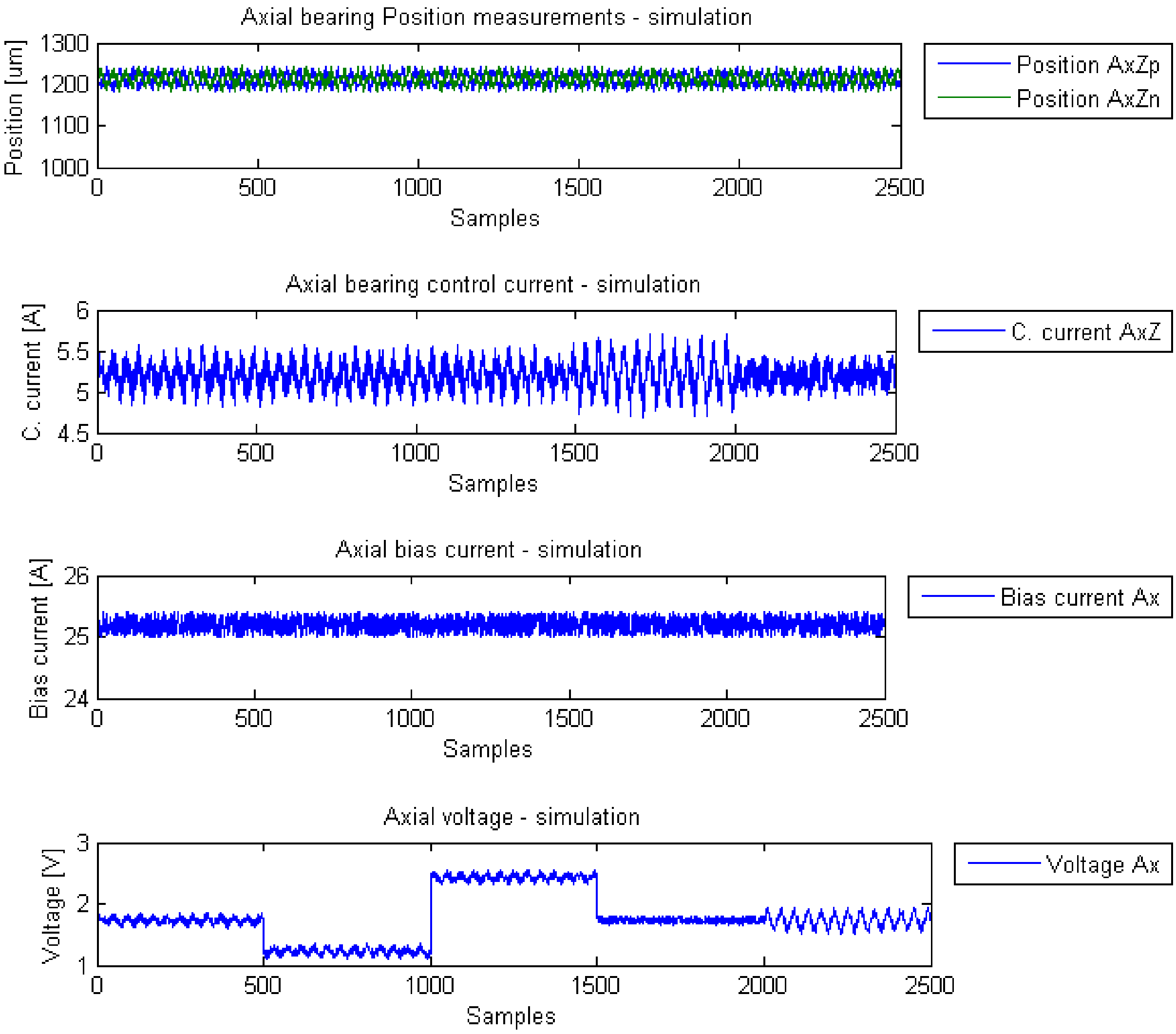


Figure 34 – Test 10, simulated signals

Table 38 – Test 10 processing of signals

Sensor diagnostics - simulation	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Mean voltage [V]	1.734	1.231	2.435	1.736	1.736
Effective value of voltage [V]	0.061	0.078	0.06	0.039	0.111
Position mean value axial z [µm]	0.197	-0.804	0.498	-0.599	0.615
Position effective value axial z [µm]	12.922	12.787	12.857	12.6721	13.026
Mean b. current axial [A]	25.197	25.2	25.2	25.201	25.196
Mean force [N]	4819.16	4795.76	4821.39	4809.37	4812.66
Mean c. current axial [A]	5.207	5.186	5.208	5.2	5.199
Axial c. current effective value [A]	0.157	0.166	0.157	0.227	0.131
A ratio	0.392	0.47	0.383	0.172	0.843
Mean voltage - small	0	0.538	0	0	0
Mean voltage - normal	1	0.462	0.566	1	1
Mean voltage - big	0	0	0.434	0	0
Mean force membership value - small	0	0	0	0	0
Mean force membership value - normal	1	1	0.947	0.977	0.968
Mean force membership value - big	0	0	0.053	0.023	0.032
A ratio membership value - small	0	0	0	1	0
A ratio membership value - normal	1	0.865	1	0	0
A ratio membership value - big	0	0.135	0	0	1
Fuzzy sum for ECS1P	0	0.538	0	0	0
Fuzzy sum for ECS1N	0	0	0.411	0	0
Fuzzy sum for ECS2P	0	0	0	1	0
Fuzzy sum for ECS2N	0	0.135	0	0	1
Error ECS1P	FALSE	TRUE	FALSE	FALSE	FALSE
Error ECS1N	FALSE	FALSE	TRUE	FALSE	FALSE
Error ECS2P	FALSE	FALSE	FALSE	TRUE	FALSE
Error ECS2N	FALSE	FALSE	FALSE	FALSE	TRUE

First data part has all normal membership values equal to 1, thus no error is detected. In the second and third part is changed offset of mean voltage from small to high value. Small mean voltage is responsible for ECS1P error and high voltage responsible for ECS2N error. Third and fourth data set includes such effective values of voltage and control current that A ratio goes from small to big value. Errors ECS2P and ECS2N are caused and recognised by this A ratio changes.

11.2.4. Test 11 – Bias current diagnostics, simulation

When normal membership value of mean voltage is dominant, bias current errors can be caused by shifting mean value of measured bias current.

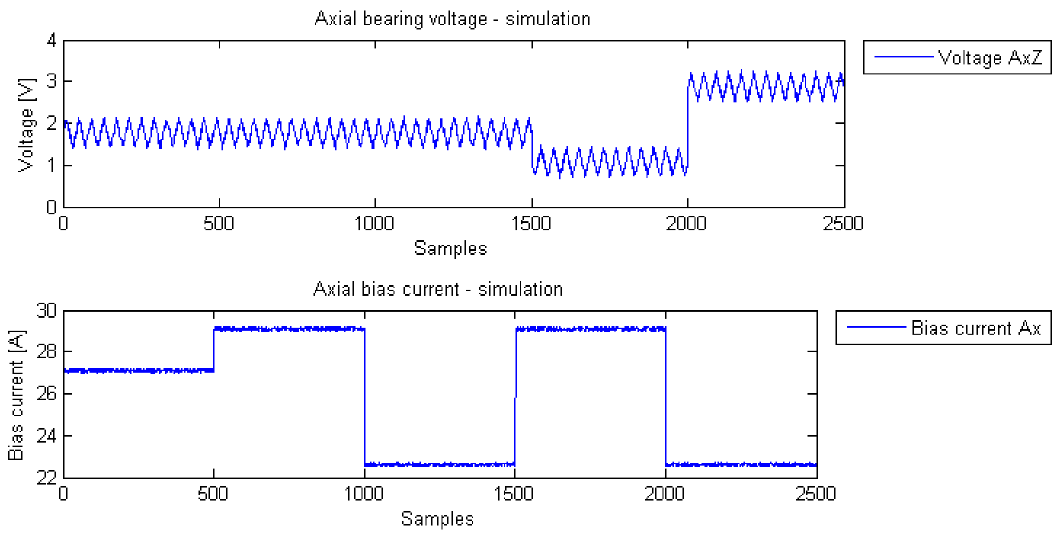


Figure 35 – Test 11, simulated signals

Table 39 – Test 11 processing of signals

Bias current diagnostics - simulation	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Voltage mean value z [V]	1.779	1.762	1.779	1.072	2.878
Mean value axial b. current [A]	27.104	29.089	22.61	29.085	22.599
Membership value – mean voltage z small	0	0	0	0.857	0
Membership value – mean voltage z normal	1	1	1	0.143	0.122
Membership value – mean voltage z big	0	0	0	0	0.878
Membership value – mean value axial bias current small	0	0	0.695	0	0.701
Membership value – mean value axial bias current normal	1	0.455	0.305	0.458	0.299
Membership value – mean value axial bias current big	0	0.545	0	0.542	0
Fuzzy sum for EBC1P	0	0.545	0	0.078	0
Fuzzy sum for EBC1N	0	0	0.695	0	0.086
Error EBC1P	FALSE	TRUE	FALSE	FALSE	FALSE
Error EBC1N	FALSE	FALSE	TRUE	FALSE	FALSE

First data part contains data where bias current is “normal” as well as mean value of voltage. Following two data parts carries bias current with positive and negative offset. These offsets cause errors EBC1P and EBC1N. Last two data parts also includes bias current with offset, but mean value of voltage is not “sufficiently normal” for causing of errors.

11.2.5. Test 12 – Bearing current diagnostics, simulation

Bearing current diagnostics is very similar to bias current diagnostics. Input signals are same, but error calculation rules are different. Mean value of voltage as well as mean value of bias current cannot be fully “normal” to cause an control current error. In this test, data part includes all possible combination of “big” and “small” membership values of mean voltage and bias current.

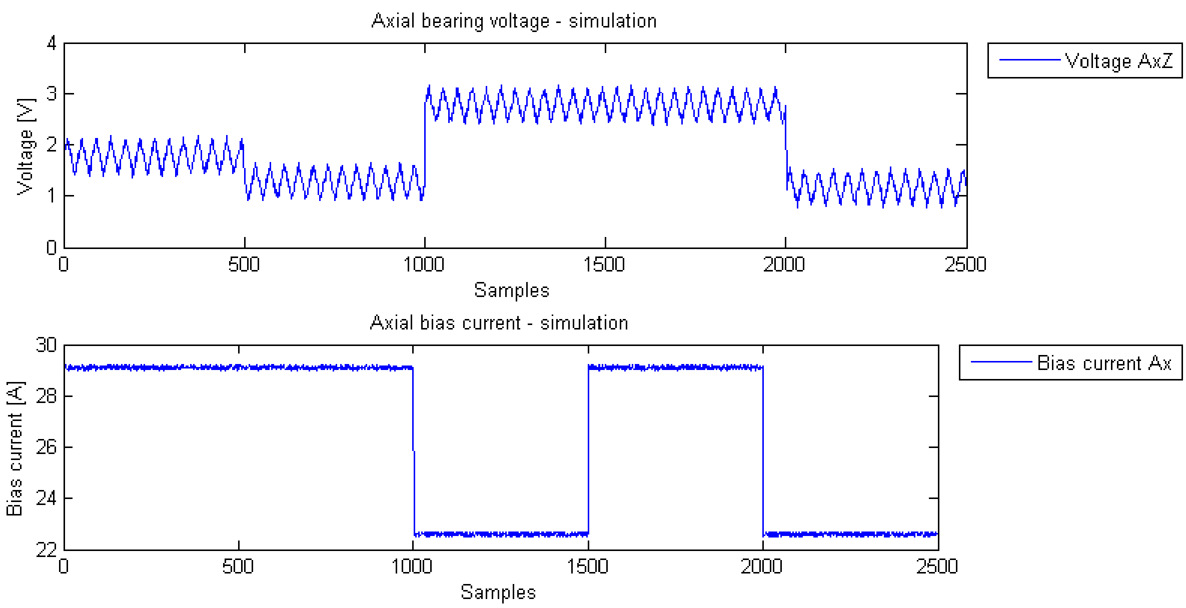


Figure 36 – Test 12, simulated signals

Table 40 – Test 12 processing of signals

Control current diagnostics - simulation	Data part 1	Data part 2	Data part 3	Data part 4	Data part 5
Voltage mean value z [V]	1.776	1.269	2.78	2.761	1.178
Mean value axial b. current [A]	29.1	29.089	22.616	29.086	22.6
Membership value – mean voltage z small	0	0.462	0	0	0.644
Membership value – mean voltage z normal	1	0.538	0.22	0.239	0.356
Membership value – mean voltage z big	0	0	0.78	0.761	0
Membership value – mean value axial bias current small	0	0	0.692	0	0.7
Membership value – mean value axial bias current normal	0.45	0.456	0.308	0.457	0.3
Membership value – mean value axial bias current big	0.55	0.544	0	0.543	0
Fuzzy sum for ECC1P	0	0.252	0	0	0
Fuzzy sum for ECC1N	0	0	0.54	0	0
Fuzzy sum for ECC2P	0	0	0	0.413	0
Fuzzy sum for ECC2N	0	0	0	0	0.451
Error ECC1P	FALSE	TRUE	FALSE	FALSE	FALSE
Error ECC1N	FALSE	FALSE	TRUE	FALSE	FALSE
Error ECC2P	FALSE	FALSE	FALSE	TRUE	FALSE
Error ECC2N	FALSE	FALSE	FALSE	FALSE	TRUE

The first data part contains relatively “big” bias current but “normal” mean value of voltage, hence no error can be detected. Following four data parts includes combinations of “big” and “small” mean values of voltage and bias current. For every combination different error is detected.

11.3. Verification of server-client communication

As mentioned above, maglap++ was not prepared to addition of diagnostic program during writing this thesis. Extra code was added to the diagnostic program to test server-client communication with android application. Android application run on android virtual device – virtual smart phone Nexus One. Communication was tested with results from tests above. As an example of testing, main screen of android app during test 7 is displayed on the following figure.

Figure 37 – Main activity during test 7

All information were successfully transferred and displayed to the user.

12. Discussion

Performed tests showed us that the diagnostic program is able to detect errors described in dissertation work of Dr.-Ing. Steffen Gärtner. Furthermore, some new error detection methods were added (for example temperature diagnostics).

However, there is still big room for improvement and especially for testing of diagnostic program. As a suggestion, I would like to mention inverted position signal in test 5. This error was not detected, but already I can think about ways how to improve diagnostics algorithm. For example, new method can be added to VPM that can calculate AC effective value of shaft's size changes. Then it would be simple to add new limit flag with new error to diagnostics. Next area that should be improved is detection of empty values in signals. Now are converted to zero values and cause false errors (for example, some errors in test 3). More real measurements from AMB systems are necessary to precisely set limit values. I would like to remind limit values for AC effective values of positions, that were too large for proper function of "Effective value of position is minimal or zero" limit flags. This problem can be solved easily by modification of limit values in configuration file. For complete verification of FLMM is necessary professional knowledge of given AMB to correctly set fuzzy sets and recorded signals with real errors. Very useful would be mathematical model that allows very detailed setting of every component of AMB system. Resulting signals from this model could be used as inputs for the diagnostics program. Another improvement can be reached by inserting control commands from AMBs into the program. This improvement may lead to eliminate false errors detection during lifting of the shaft (critical position errors in second data part of the test 7). Visualisation app can be extended to new functions e.g. direct selection of diagnostic methods.

I believe this list of improvements can be further extended, but it should not be seen as weaknesses in my work, because all objectives were successfully completed. This list should be seen as suggestions for further development of AMB's diagnostic software, that go beyond scope of this work.

For writing diagnostic program was used open source integrated development environment (IDE) Code::Blocks. For android application writing was used official IDE – Android Studio. Pictures presented in this thesis are drawn in Zoner Calisto 5, Inkscape or Dia software.

13. Conclusion

Active magnetic bearings are typical mechatronic devices composed of mechanical, electrical and information processing parts. Complexity of these devices makes high demands on their operation. The diagnostic program, main product of this work, consist of more than 8000 (including visualisation application) lines of code and includes successfully implemented diagnostic methods from dissertation work of Dr.-Ing. Steffen Gärtner. These methods are furthermore extended by few more diagnostic possibilities described in chapters of this thesis. Verification of the program was made by data from MFLP device added by simulated signals.

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List of appendices

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Appendix A – List of limit flags

Table 41 – Limit flags for axial bearing

Variable name	Attribute	Active when	Commentary
Vb_lf_pCrit_az	$\lvert s_z \rvert$	Exceed	Critical position on z axis
Vb_lf_pSensOver_azp	s_z	Combined conditions	Sensor over range in positive direction
Vb_lf_pSensOver_azn	s_z	Combined conditions	Sensor over range in negative direction
Vb_lf_pInR_az	$\lvert \bar{s_z} \rvert$	Fall below	Position in normal working range
Vb_lf_pRB_az	$\overline{\lvert \bar{s_z} \rvert}$	Exceed	Shaft in back up bearings
Vb_lf_pAC_az	$\tilde{s_z}$	Fall below	AC effective value of position signal below limit
Vb_lf_pG2H_az	$\lvert \Delta s_z \rvert * f_s$	Exceed	Position gradient too high
Vb_lf_iMinMean_az	$\lvert \bar{\imath}_{az} \rvert$	Fall below	Control current in coil is zero or very small
Vb_lf_iMaxMean_az	$\lvert \bar{\imath}_{az} \rvert$	Exceed	Control current in coil is too big, shortcut
Vb_lf_iAC_az	$\widetilde{\imath_{az}}$	Fall below	AC effective value of control current below limit
Vb_lf_iCrit_az	$\lvert i_{az} \rvert$	Exceed	Shortcut – peak value of control current can be detected, electronics can be damaged
Vb_lf_t1Max_a	$\bar{t}_a$	Exceed	Temperature too high
Vb_lf_t2Max_a	$\bar{t_a}$	Exceed	Temperature too high
Vb_lf_t3Max_a	$\bar{t_a}$	Exceed	Temperature too high
Vb_lf_t4Max_a	$\bar{t_a}$	Exceed	Temperature too high
Vb_lf_t5Max_a	$\bar{t_a}$	Exceed	Temperature too high
Vb_lf_t6Max_a	$\bar{t_a}$	Exceed	Temperature too high
Vb_lf_t7Max_a	$\bar{t_a}$	Exceed	Temperature too high
Vb_lf_t8Max_a	$\bar{t_a}$	Exceed	Temperature too high
Vb_LiMo_lf_t1SensError_a	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t2SensError_a	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t3SensError_a	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t4SensError_a	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t5SensError_a	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t6SensError_a	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t7SensError_a	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t8SensError_a	Combined attributes	Combined conditions	Temperature sensor error

Table 42 – Limit flags for radial bearings

Variable name	Attribute	Active when	Commentary
Vb_lf_pCrit_rxy	$\lvert s_{xy} \rvert$	Exceed	Critical position in radial bearing
Vb_lf_pSensOver_rxp	s_{xp}	Combined conditions	Sensor over range in x positive direction
Vb_lf_pSensOver_rxn	s_{xn}	Combined conditions	Sensor over range in x negative direction
Vb_lf_pSensOver_ryp	s_{yp}	Combined conditions	Sensor over range in y positive direction
Vb_lf_pSensOver_ryn	s_{yn}	Combined conditions	Sensor over range in y negative direction
Vb_lf_pInR_rxy	$\lvert \overline{s_{xy}} \rvert$	Fall below	Position in normal working range
Vb_lf_pRB_rxy	$\lvert \overline{s_{xy}} \rvert$	Exceed	Position in back up bearings
Vb_lf_pAC_rxy	Combined attributes	Fall below	AC effective value of position below limit
Vb_lf_pG2H_rxy	Combined attributes	Combined conditions	Position gradient too high
Vb_lf_iMinMean_rx	$\lvert \bar{\iota}_{rx} \rvert$	Fall below	Control current in coil is zero or very small
Vb_lf_iMinMean_ry	$\lvert \bar{\iota}_{ry} \rvert$	Fall below	Control current in coil is zero or very small
Vb_lf_iMaxMean_rx	$\lvert \bar{\iota}_{rx} \rvert$	Exceed	Control current in coil is too big, shortcut
Vb_lf_iMaxMean_ry	$\lvert \bar{\iota}_{ry} \rvert$	Exceed	Control current in coil is too big, shortcut
Vb_lf_iAC_rx	$\widetilde{\iota_{rx}}$	Fall below	AC effective value of control current below limit
Vb_lf_iAC_ry	$\widetilde{\iota_{ry}}$	Fall below	AC effective value of control current below limit
Vb_lf_iCrit_rx	$\lvert i_{rx} \rvert$	Exceed	Shortcut – peak value of control current can be detected, electronics can be damaged
Vb_lf_iCrit_ry	$\lvert i_{ry} \rvert$	Exceed	Shortcut – peak value of control current can be detected, electronics can be damaged
Vb_lf_t1Max_r	$\bar{t}_{\mathrm{r}}$	Exceed	Temperature too high
Vb_lf_t2Max_r	$\bar{t}_{\mathrm{r}}$	Exceed	Temperature too high
Vb_lf_t3Max_r	$\bar{t}_{\mathrm{r}}$	Exceed	Temperature too high
Vb_lf_t4Max_r	$\bar{t}_{\mathrm{r}}$	Exceed	Temperature too high
Vb_lf_t5Max_r	$\bar{t}_{\mathrm{r}}$	Exceed	Temperature too high
Vb_lf_t6Max_r	$\bar{t}_{\mathrm{r}}$	Exceed	Temperature too high
Vb_lf_t7Max_r	$\bar{t}_{\mathrm{r}}$	Exceed	Temperature too high
Vb_lf_t8Max_r	$\bar{t}_{\mathrm{r}}$	Exceed	Temperature too high
Vb_LiMo_lf_t1SensError_r	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t2SensError_r	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t3SensError_r	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t4SensErro_r	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t5SensError_r	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t6SensError_r	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t7SensError_r	Combined attributes	Combined conditions	Temperature sensor error
Vb_LiMo_lf_t8SensError_r	Combined attributes	Combined conditions	Temperature sensor error

Table 43 – Other limit flags

Variable name	Attribute	Active when	Commentary
Vb_lf_nRot2H	$\lvert\bar{n}\rvert$	Exceed	Speed of shaft is too high
Vb_lf_nRot2L	$\lvert\bar{n}\rvert$	Exceed	Speed of shaft is too low
Vb_lf_nRot0	$\overline{\lvert n\rvert}$	Fall below	Shaft is not rotating
Vb_lf_nAcc	$(\Delta\lvert\bar{n}\rvert)/(n_s/f_s)$	Exceed	Shaft is accelerating
Vb_lf_nDec	$(\Delta\lvert\bar{n}\rvert)/(n_s/f_s)$	Fall below	Shaft is decelerating
Vd_LiMo_lv_iBMaxMean_a	$\bar{\imath}_{ab}$	Exceed	Mean value of bias current too high
Vd_LiMo_lv_iBMax_a	i_{ab}	Exceed	Peak value of bias current is too high
Vd_LiMo_lv_iBMaxMean_r	$\bar{\imath}_{rb}$	Exceed	Mean value of bias current too high
Vd_LiMo_lv_iBMax_r	i_{rb}	Exceed	Peak value of bias current is too high
Vd_LiMo_lv_iBMinMean_a	$\bar{\imath}_{ab}$	Fall below	Mean value of bias current below limit
Vd_LiMo_lv_iBMinMean_a	$\bar{\imath}_{rb}$	Fall below	Mean value of bias current below limit

Appendix B – configuration file

```
[Limits]

Vd_LiMo_lv_pCrit_az = 200
Vd_LiMo_lv_pSensOver_azpb = 2000
Vd_LiMo_lv_pSensOver_aznb = 2000
Vd_LiMo_lv_pSensOver_azps = 0
Vd_LiMo_lv_pSensOver_azns = 0
Vd_LiMo_lv_pInR_az = 100
Vd_LiMo_lv_pRB_az = 250
Vd_LiMo_lv_pAC_az = 15
Vd_LiMo_lv_pG2H_az = 11000

Vd_LiMo_lv_iMinMean_az = 0.1
Vd_LiMo_lv_iMaxMean_az = 30
Vd_LiMo_lv_iAC_az = 0.3
Vd_LiMo_lv_iCrit_az = 35

Vd_LiMo_lv_t1Crit_a = 125
Vd_LiMo_lv_t2Crit_a = 125
Vd_LiMo_lv_t3Crit_a = 125
Vd_LiMo_lv_t4Crit_a = 125
Vd_LiMo_lv_t5Crit_a = 125
Vd_LiMo_lv_t6Crit_a = 125
Vd_LiMo_lv_t7Crit_a = 125
Vd_LiMo_lv_t8Crit_a = 125
Vd_LiMo_lv_t1SensOver_ap = 1000
Vd_LiMo_lv_t2SensOver_ap = 1000
Vd_LiMo_lv_t3SensOver_ap = 1000
Vd_LiMo_lv_t4SensOver_ap = 1000
Vd_LiMo_lv_t5SensOver_ap = 1000
Vd_LiMo_lv_t6SensOver_ap = 1000
Vd_LiMo_lv_t7SensOver_ap = 1000
Vd_LiMo_lv_t8SensOver_ap = 1000

Vd_LiMo_lv_t1SensOver_an = -20
Vd_LiMo_lv_t2SensOver_an = -20
Vd_LiMo_lv_t3SensOver_an = -20
Vd_LiMo_lv_t4SensOver_an = -20
Vd_LiMo_lv_t5SensOver_an = -20
Vd_LiMo_lv_t6SensOver_an = -20
Vd_LiMo_lv_t7SensOver_an = -20
Vd_LiMo_lv_t8SensOver_an = -20

Vd_LiMo_lv_t1G2H_a = 2000
Vd_LiMo_lv_t2G2H_a = 2000
Vd_LiMo_lv_t3G2H_a = 2000
Vd_LiMo_lv_t4G2H_a = 2000
Vd_LiMo_lv_t5G2H_a = 2000
Vd_LiMo_lv_t6G2H_a = 2000
Vd_LiMo_lv_t7G2H_a = 2000
Vd_LiMo_lv_t8G2H_a = 2000

Vd_LiMo_lv_pCrit_rxy = 200
Vd_LiMo_lv_pSensOver_rxpb = 2000
Vd_LiMo_lv_pSensOver_rxnb = 2000
Vd_LiMo_lv_pSensOver_rypb = 2000
Vd_LiMo_lv_pSensOver_rynb = 2000
Vd_LiMo_lv_pSensOver_rxps = 0
```

```
Vd_LiMo_lv_pSensOver_rxns = 0
Vd_LiMo_lv_pSensOver_ryps = 0
Vd_LiMo_lv_pSensOver_ryns = 0
Vd_LiMo_lv_pInR_rxy = 100
Vd_LiMo_lv_pRB_rxy = 250
Vd_LiMo_lv_pAC_rxy = 15
Vd_LiMo_lv_pG2H_rxy = 11000

Vd_LiMo_lv_iMinMean_rx = 0.1
Vd_LiMo_lv_iMinMean_ry = 0.1
Vd_LiMo_lv_iMaxMean_rx = 30
Vd_LiMo_lv_iMaxMean_ry = 30
Vd_LiMo_lv_iAC_rx = 0.3
Vd_LiMo_lv_iAC_ry = 0.3
Vd_LiMo_lv_iCrit_rx = 35
Vd_LiMo_lv_iCrit_ry = 35

Vd_LiMo_lv_t1Crit_r = 125
Vd_LiMo_lv_t2Crit_r = 125
Vd_LiMo_lv_t3Crit_r = 125
Vd_LiMo_lv_t4Crit_r = 125
Vd_LiMo_lv_t5Crit_r = 125
Vd_LiMo_lv_t6Crit_r = 125
Vd_LiMo_lv_t7Crit_r = 125
Vd_LiMo_lv_t8Crit_r = 125

Vd_LiMo_lv_t1SensOver_rp = 1000
Vd_LiMo_lv_t2SensOver_rp = 1000
Vd_LiMo_lv_t3SensOver_rp = 1000
Vd_LiMo_lv_t4SensOver_rp = 1000
Vd_LiMo_lv_t5SensOver_rp = 1000
Vd_LiMo_lv_t6SensOver_rp = 1000
Vd_LiMo_lv_t7SensOver_rp = 1000
Vd_LiMo_lv_t8SensOver_rp = 1000

Vd_LiMo_lv_t1SensOver_rn = -20
Vd_LiMo_lv_t2SensOver_rn = -20
Vd_LiMo_lv_t3SensOver_rn = -20
Vd_LiMo_lv_t4SensOver_rn = -20
Vd_LiMo_lv_t5SensOver_rn = -20
Vd_LiMo_lv_t6SensOver_rn = -20
Vd_LiMo_lv_t7SensOver_rn = -20
Vd_LiMo_lv_t8SensOver_rn = -20

Vd_LiMo_lv_t1G2H_r = 2000
Vd_LiMo_lv_t2G2H_r = 2000
Vd_LiMo_lv_t3G2H_r = 2000
Vd_LiMo_lv_t4G2H_r = 2000
Vd_LiMo_lv_t5G2H_r = 2000
Vd_LiMo_lv_t6G2H_r = 2000
Vd_LiMo_lv_t7G2H_r = 2000
Vd_LiMo_lv_t8G2H_r = 2000

Vd_LiMo_lv_nRot0 = 10
Vd_LiMo_lv_nRot2H = 4100
Vd_LiMo_lv_nRot2L = 3600
Vd_LiMo_lv_nAcc = 10
Vd_LiMo_lv_nDec = -10

Vd_LiMo_lv_iBMaxMean_a = 30
Vd_LiMo_lv_iBMax_a = 35
Vd_LiMo_lv_iBMinMean_a = 0.1
```

```
Vd_LiMo_lv_iBMaxMean_r = 30
Vd_LiMo_lv_iBMax_r = 35
Vd_LiMo_lv_iBMinMean_r = 0.1

[Fuzzysets]

Vd_DaMa_ErrThreshold = 0.2

Vd_DaMa_NomAirGapAx = 250
Vd_DaMa_CoilConstAx = 0.05049
Vd_DaMa_V1Ax = 0.005
Vd_DaMa_V2Ax = 0.005

Vd_DaMa_NomAirGapRa = 250
Vd_DaMa_CoilConstRa = 0.05049
Vd_DaMa_V1Ra = 0.005
Vd_DaMa_V2Ra = 0.005

Vd_MeanForAxRd_S0 = 4400
Vd_MeanForAxRd_S1 = 3800
Vd_MeanForAxRd_B0 = 4800
Vd_MeanForAxRd_B1 = 5200

Vd_WAxRd_S0 = 0.02
Vd_WAxRd_S1 = 0.01
Vd_WAxRd_B0 = 0.024
Vd_WAxRd_B1 = 0.034

Vd_MeanCCurAxRd_S0 = 4
Vd_MeanCCurAxRd_S1 = 2.5
Vd_MeanCCurAxRd_B0 = 6
Vd_MeanCCurAxRd_B1 = 10

Vd_ACForAxRd_S0 = 250
Vd_ACForAxRd_S1 = 170
Vd_ACForAxRd_B0 = 400
Vd_ACForAxRd_B1 = 480

Vd_MeanVolAxRd_S0 = 1.5
Vd_MeanVolAxRd_S1 = 1
Vd_MeanVolAxRd_B0 = 2
Vd_MeanVolAxRd_B1 = 3

Vd_RAxRd_S0 = 45
Vd_RAxRd_S1 = 30
Vd_RAxRd_B0 = 55
Vd_RAxRd_B1 = 70

Vd_MeanPosAxRd_S0 = -50
Vd_MeanPosAxRd_S1 = -100
Vd_MeanPosAxRd_B0 = 50
Vd_MeanPosAxRd_B1 = 100

Vd_MeanBCurAxRd_S0 = 24
Vd_MeanBCurAxRd_S1 = 22
Vd_MeanBCurAxRd_B0 = 28
Vd_MeanBCurAxRd_B1 = 30

Vd_AAxRd_S0 = 0.3
Vd_AAxRd_S1 = 0.2
Vd_AAxRd_B0 = 0.45
Vd_AAxRd_B1 = 0.6
```

```
Vd_MeanForRaRd_S0 = 4400
Vd_MeanForRaRd_S1 = 3800
Vd_MeanForRaRd_B0 = 4800
Vd_MeanForRaRd_B1 = 5200

Vd_WRaRd_S0 = 0.02
Vd_WRaRd_S1 = 0.01
Vd_WRaRd_B0 = 0.024
Vd_WRaRd_B1 = 0.034

Vd_MeanCCurRaRd_S0 = 4
Vd_MeanCCurRaRd_S1 = 2.5
Vd_MeanCCurRaRd_B0 = 6
Vd_MeanCCurRaRd_B1 = 10

Vd_ACForRaRd_S0 = 250
Vd_ACForRaRd_S1 = 170
Vd_ACForRaRd_B0 = 400
Vd_ACForRaRd_B1 = 480

Vd_MeanVolRaRd_S0 = 1.5
Vd_MeanVolRaRd_S1 = 1
Vd_MeanVolRaRd_B0 = 2
Vd_MeanVolRaRd_B1 = 3

Vd_RRaRd_S0 = 45
Vd_RRaRd_S1 = 30
Vd_RRaRd_B0 = 55
Vd_RRaRd_B1 = 70

Vd_MeanPosRaRd_S0 = -50
Vd_MeanPosRaRd_S1 = -100
Vd_MeanPosRaRd_B0 = 50
Vd_MeanPosRaRd_B1 = 100

Vd_MeanBCurRaRd_S0 = 24
Vd_MeanBCurRaRd_S1 = 22
Vd_MeanBCurRaRd_B0 = 28
Vd_MeanBCurRaRd_B1 = 30

Vd_ARaRd_S0 = 0.3
Vd_ARaRd_S1 = 0.2
Vd_ARaRd_B0 = 0.45
Vd_ARaRd_B1 = 0.6
```

Appendix C – Order of limit flags and fuzzy errors in vectors

Table 44 – Order of limit flags in limit flags vector

Position	Limit flag	Group	Position in group
0	Vb_LiMo_lf_pCrit_az	Axial position LFs	0
1	Vb_LiMo_lf_pSensOver_azp		1
2	Vb_LiMo_lf_pSensOver_azn		2
3	Vb_LiMo_lf_pInR_az		3
4	Vb_LiMo_lf_pRB_az		4
5	Vb_LiMo_lf_pAC_az		5
6	Vb_LiMo_lf_pG2H_az		6
7	Vb_LiMo_lf_iMinMean_azp	Axial control current LFs	0
9	Vb_LiMo_lf_iMaxMean_azp		1
11	Vb_LiMo_lf_iAC_azp		2
13	Vb_LiMo_lf_iCrit_azp		3
15	Vb_LiMo_lf_t1Crit_a	Axial temperature LFs	0
16	Vb_LiMo_lf_t2Crit_a		1
17	Vb_LiMo_lf_t3Crit_a		2
18	Vb_LiMo_lf_t4Crit_a		3
19	Vb_LiMo_lf_t5Crit_a		4
20	Vb_LiMo_lf_t6Crit_a		5
21	Vb_LiMo_lf_t7Crit_a		6
22	Vb_LiMo_lf_t8Crit_a		7
23	Vb_LiMo_lf_t1SensError_a		8
24	Vb_LiMo_lf_t2SensError_a		9
25	Vb_LiMo_lf_t3SensError_a		10
26	Vb_LiMo_lf_t4SensError_a		11
27	Vb_LiMo_lf_t5SensError_a		12
28	Vb_LiMo_lf_t6SensError_a		13
29	Vb_LiMo_lf_t7SensError_a		14
30	Vb_LiMo_lf_t8SensError_a		15
31	Vb_LiMo_lf_pCrit_rxy	Radial 1 position LFs	0
32	Vb_LiMo_lf_pSensOver_rxp		1
33	Vb_LiMo_lf_pSensOver_rxn		2
34	Vb_LiMo_lf_pSensOver_ryp		3
35	Vb_LiMo_lf_pSensOver_ryn		4
36	Vb_LiMo_lf_pInR_rxy		5
37	Vb_LiMo_lf_pRB_rxy		6
38	Vb_LiMo_lf_pAC_rxy		7
39	Vb_LiMo_lf_pG2H_rxy		8
40	Vb_LiMo_lf_iMinMean_rxp	Radial 1 control current LFs	0
42	Vb_LiMo_lf_iMinMean_ryp		1
44	Vb_LiMo_lf_iMaxMean_rxp		2

46	Vb_LiMo_lf_iMaxMean_ryp		3
48	Vb_LiMo_lf_iAC_rxp		4
50	Vb_LiMo_lf_iAC_ryp		5
52	Vb_LiMo_lf_iCrit_rxp		6
54	Vb_LiMo_lf_iCrit_ryp		7
56	Vb_LiMo_lf_t1Crit_r	Radial 1 temperature LFs	0
57	Vb_LiMo_lf_t2Crit_r		1
58	Vb_LiMo_lf_t3Crit_r		2
59	Vb_LiMo_lf_t4Crit_r		3
60	Vb_LiMo_lf_t5Crit_r		4
61	Vb_LiMo_lf_t6Crit_r		5
62	Vb_LiMo_lf_t7Crit_r		6
63	Vb_LiMo_lf_t8Crit_r		7
64	Vb_LiMo_lf_t1SensError_r		8
65	Vb_LiMo_lf_t2SensError_r		9
66	Vb_LiMo_lf_t3SensError_r		10
67	Vb_LiMo_lf_t4SensError_r		11
68	Vb_LiMo_lf_t5SensError_r		12
69	Vb_LiMo_lf_t6SensError_r		13
70	Vb_LiMo_lf_t7SensError_r		14
71	Vb_LiMo_lf_t8SensError_r		15
72	Vb_LiMo_lf_pCrit_rxy	Radial 2 position LFs	0
73	Vb_LiMo_lf_pSensOver_rxp		1
74	Vb_LiMo_lf_pSensOver_rxn		2
75	Vb_LiMo_lf_pSensOver_ryp		3
76	Vb_LiMo_lf_pSensOver_ryn		4
77	Vb_LiMo_lf_pInR_rxy		5
78	Vb_LiMo_lf_pRB_rxy		6
79	Vb_LiMo_lf_pAC_rxy		7
80	Vb_LiMo_lf_pG2H_rxy		8
81	Vb_LiMo_lf_iMinMean_rxp	Radial 2 control current LFs	0
83	Vb_LiMo_lf_iMinMean_ryp		1
85	Vb_LiMo_lf_iMaxMean_rxp		2
87	Vb_LiMo_lf_iMaxMean_ryp		3
89	Vb_LiMo_lf_iAC_rxp		4
91	Vb_LiMo_lf_iAC_ryp		5
93	Vb_LiMo_lf_iCrit_rxp		6
95	Vb_LiMo_lf_iCrit_ryp		7
97	Vb_LiMo_lf_t1Crit_r	Radial 2 temperature LFs	0
98	Vb_LiMo_lf_t2Crit_r		1
99	Vb_LiMo_lf_t3Crit_r		2
100	Vb_LiMo_lf_t4Crit_r		3
101	Vb_LiMo_lf_t5Crit_r		4
102	Vb_LiMo_lf_t6Crit_r		5
103	Vb_LiMo_lf_t7Crit_r		6

104	Vb_LiMo_lf_t8Crit_r		7
105	Vb_LiMo_lf_t1SensError_r		8
106	Vb_LiMo_lf_t2SensError_r		9
107	Vb_LiMo_lf_t3SensError_r		10
108	Vb_LiMo_lf_t4SensError_r		11
109	Vb_LiMo_lf_t5SensError_r		12
110	Vb_LiMo_lf_t6SensError_r		13
111	Vb_LiMo_lf_t7SensError_r		14
112	Vb_LiMo_lf_t8SensError_r		15
113	Vb_LiMo_lf_nRot2H	Rotation LFs	0
114	Vb_LiMo_lf_nRot2L		1
115	Vb_LiMo_lf_nRot0		2
116	Vb_LiMo_lf_nAcc		3
117	Vb_LiMo_lf_nDec		4
118	Vb_LiMo_lf_iBMaxMean_a	Axial bias current LFs	0
119	Vb_LiMo_lf_iBMax_a		1
120	Vb_LiMo_lf_iBMinMean_a		2
121	Vb_LiMo_lf_iBMaxMean_r	Radial bias current LFs	0
122	Vb_LiMo_lf_iBMax_r		1
123	Vb_LiMo_lf_iBMinMean_r		2

Table 45 – Order of errors in fuzzy errors vector

Position	Error	Group	Position in group
0	Vb_FuzMo_Err_ES1P	Axial deflection sensors	0
1	Vb_FuzMo_Err_ES1N		1
2	Vb_FuzMo_Err_ES2P		2
3	Vb_FuzMo_Err_ES2N		3
4	Vb_FuzMo_Err_EC1P	Axial controller	0
5	Vb_FuzMo_Err_EC1N		1
6	Vb_FuzMo_Err_EC2P		2
7	Vb_FuzMo_Err_EC2N		3
8	Vb_FuzMo_Err_ECS1P	Axial control signal	0
9	Vb_FuzMo_Err_ECS1N		1
10	Vb_FuzMo_Err_ECS2P		2
11	Vb_FuzMo_Err_ECS2N		3
12	Vb_FuzMo_Err_EBC1P	Axial bias current	0
13	Vb_FuzMo_Err_EBC1N		1
14	Vb_FuzMo_Err_ECC1P	Axial bearing current	0
15	Vb_FuzMo_Err_ECC1N		1
16	Vb_FuzMo_Err_ECC2P		2
17	Vb_FuzMo_Err_ECC2N		3
18	Vb_FuzMo_Err_ES1P	Radial 1 deflection sensors	0
19	Vb_FuzMo_Err_ES1N		1
20	Vb_FuzMo_Err_ES2P		2

21	Vb_FuzMo_Err_ES2N		3
22	Vb_FuzMo_Err_ES1P		4
23	Vb_FuzMo_Err_ES1N		5
24	Vb_FuzMo_Err_ES2P		6
25	Vb_FuzMo_Err_ES2N		7
26	Vb_FuzMo_Err_EC1P	Radial 1 controller	0
27	Vb_FuzMo_Err_EC1N		1
28	Vb_FuzMo_Err_EC2P		2
29	Vb_FuzMo_Err_EC2N		3
30	Vb_FuzMo_Err_EC1P		4
31	Vb_FuzMo_Err_EC1N		5
32	Vb_FuzMo_Err_EC2P		6
33	Vb_FuzMo_Err_EC2N		7
34	Vb_FuzMo_Err_ECS1P	Radial 1 control signal	0
35	Vb_FuzMo_Err_ECS1N		1
36	Vb_FuzMo_Err_ECS2P		2
37	Vb_FuzMo_Err_ECS2N		3
38	Vb_FuzMo_Err_ECS1P		4
39	Vb_FuzMo_Err_ECS1N		5
40	Vb_FuzMo_Err_ECS2P		6
41	Vb_FuzMo_Err_ECS2N		7
42	Vb_FuzMo_Err_EBC1P	Radial 1 Bias current	0
43	Vb_FuzMo_Err_EBC1N		1
44	Vb_FuzMo_Err_EBC1P		2
45	Vb_FuzMo_Err_EBC1N		3
46	Vb_FuzMo_Err_ECC1P	Radial 1 Control current	0
47	Vb_FuzMo_Err_ECC1N		1
48	Vb_FuzMo_Err_ECC2P		2
49	Vb_FuzMo_Err_ECC2N		3
50	Vb_FuzMo_Err_ECC1P		4
51	Vb_FuzMo_Err_ECC1N		5
52	Vb_FuzMo_Err_ECC2P		6
53	Vb_FuzMo_Err_ECC2N		7
54	Vb_FuzMo_Err_ES1P	Radial 2 deflection sensors	0
55	Vb_FuzMo_Err_ES1N		1
56	Vb_FuzMo_Err_ES2P		2
57	Vb_FuzMo_Err_ES2N		3
58	Vb_FuzMo_Err_ES1P		4
59	Vb_FuzMo_Err_ES1N		5
60	Vb_FuzMo_Err_ES2P		6
61	Vb_FuzMo_Err_ES2N		7
62	Vb_FuzMo_Err_EC1P	Radial 2 controller	0
63	Vb_FuzMo_Err_EC1N		1
64	Vb_FuzMo_Err_EC2P		2
65	Vb_FuzMo_Err_EC2N		3

66	Vb_FuzMo_Err_EC1P		4
67	Vb_FuzMo_Err_EC1N		5
68	Vb_FuzMo_Err_EC2P		6
69	Vb_FuzMo_Err_EC2N		7
70	Vb_FuzMo_Err_ECS1P	Radial 2 control signal	0
71	Vb_FuzMo_Err_ECS1N		1
72	Vb_FuzMo_Err_ECS2P		2
73	Vb_FuzMo_Err_ECS2N		3
74	Vb_FuzMo_Err_ECS1P		4
75	Vb_FuzMo_Err_ECS1N		5
76	Vb_FuzMo_Err_ECS2P		6
77	Vb_FuzMo_Err_ECS2N		7
78	Vb_FuzMo_Err_EBC1P	Radial 2 Bias current	0
79	Vb_FuzMo_Err_EBC1N		1
80	Vb_FuzMo_Err_EBC1P		2
81	Vb_FuzMo_Err_EBC1N		3
82	Vb_FuzMo_Err_ECC1P	Radial 2 Control current	0
83	Vb_FuzMo_Err_ECC1N		1
84	Vb_FuzMo_Err_ECC2P		2
85	Vb_FuzMo_Err_ECC2N		3
86	Vb_FuzMo_Err_ECC1P		4
87	Vb_FuzMo_Err_ECC1N		5
88	Vb_FuzMo_Err_ECC2P		6
89	Vb_FuzMo_Err_ECC2N		7

Appendix D – List of error and warning codes

Table 46 – List of error IDs, errors detected from limit flags

Error code (LMM)	Description
11110	Critical position of shaft - axial bearing
11121	Sensor over range - positive Z axis - axial bearing
11122	Sensor over range - negative Z axis - axial bearing
11130	Gradient of position too high - axial bearing
11211	Critical mean control current - positive Z axis - axial bearing
11221	Critical control current (peak values) - positive Z axis - axial bearing
11311	Critical temperature sensor 1 - axial bearing
11312	Critical temperature sensor 2 - axial bearing
11313	Critical temperature sensor 3 - axial bearing
11314	Critical temperature sensor 4 - axial bearing
11315	Critical temperature sensor 5 - axial bearing
11316	Critical temperature sensor 6 - axial bearing
11317	Critical temperature sensor 7 - axial bearing
11318	Critical temperature sensor 8 - axial bearing
11321	Sensor 1 error (over range or bad signal) - axial bearing
11322	Sensor 2 error (over range or bad signal) - axial bearing
11323	Sensor 3 error (over range or bad signal) - axial bearing
11324	Sensor 4 error (over range or bad signal) - axial bearing
11325	Sensor 5 error (over range or bad signal) - axial bearing
11326	Sensor 6 error (over range or bad signal) - axial bearing
11327	Sensor 7 error (over range or bad signal) - axial bearing
11328	Sensor 8 error (over range or bad signal) - axial bearing
12110	Critical position of shaft - radial bearing 1
12121	Sensor over range - positive X axis - Radial bearing 1
12122	Sensor over range - negative X axis - Radial bearing 1
12123	Sensor over range - positive Y axis - Radial bearing 1
12124	Sensor over range - negative Y axis - Radial bearing 1
12130	Gradient of position too high - radial bearing 1
12211	Critical mean control current - positive X axis - Radial bearing 1
12213	Critical mean control current - positive Y axis - Radial bearing 1
12221	Critical control current (peak values) - positive X axis - Radial bearing 1
12223	Critical control current (peak values) - positive Y axis - Radial bearing 1
12311	Critical temperature sensor 1 - Radial bearing 1
12312	Critical temperature sensor 2 - Radial bearing 1
12313	Critical temperature sensor 3 - Radial bearing 1
12314	Critical temperature sensor 4 - Radial bearing 1
12315	Critical temperature sensor 5 - Radial bearing 1
12316	Critical temperature sensor 6 - Radial bearing 1
12317	Critical temperature sensor 7 - Radial bearing 1

12318	Critical temperature sensor 8 - Radial bearing 1
12321	Sensor 1 error (over range or bad signal) - Radial bearing 1
12322	Sensor 2 error (over range or bad signal) - Radial bearing 1
12323	Sensor 3 error (over range or bad signal) - Radial bearing 1
12324	Sensor 4 error (over range or bad signal) - Radial bearing 1
12325	Sensor 5 error (over range or bad signal) - Radial bearing 1
12326	Sensor 6 error (over range or bad signal) - Radial bearing 1
12327	Sensor 7 error (over range or bad signal) - Radial bearing 1
12328	Sensor 8 error (over range or bad signal) - Radial bearing 1
13110	Critical position of shaft - radial bearing 2
13121	Sensor over range - positive X axis - Radial bearing 2
13122	Sensor over range - negative X axis - Radial bearing 2
13123	Sensor over range - positive Y axis - Radial bearing 2
13124	Sensor over range - negative Y axis - Radial bearing 2
13130	Gradient of position too high - radial bearing 2
13211	Critical mean control current - positive X axis - Radial bearing 2
13213	Critical mean control current - positive Y axis - Radial bearing 2
13221	Critical control current (peak values) - positive X axis - Radial bearing 2
13223	Critical control current (peak values) - positive Y axis - Radial bearing 2
13311	Critical temperature sensor 1 - Radial bearing 2
13312	Critical temperature sensor 2 - Radial bearing 2
13313	Critical temperature sensor 3 - Radial bearing 2
13314	Critical temperature sensor 4 - Radial bearing 2
13315	Critical temperature sensor 5 - Radial bearing 2
13316	Critical temperature sensor 6 - Radial bearing 2
13317	Critical temperature sensor 7 - Radial bearing 2
13318	Critical temperature sensor 8 - Radial bearing 2
13321	Sensor 1 error (over range or bad signal) - Radial bearing 2
13322	Sensor 2 error (over range or bad signal) - Radial bearing 2
13323	Sensor 3 error (over range or bad signal) - Radial bearing 2
13324	Sensor 4 error (over range or bad signal) - Radial bearing 2
13325	Sensor 5 error (over range or bad signal) - Radial bearing 2
13326	Sensor 6 error (over range or bad signal) - Radial bearing 2
13327	Sensor 7 error (over range or bad signal) - Radial bearing 2
13328	Sensor 8 error (over range or bad signal) - Radial bearing 2
14410	Rotation speed is too high
14411	Rotation speed is too low
14510	Axial bias mean current is too high
14520	Axial bias current (peak values) is too high
14610	Radial bias mean current is too high
14620	Radial bias current (peak values) is too high

Table 47 – List of error IDs, errors detected by FLMM

Error code (FLMM)	Description
21111	Offset of sensor signal, positive - axial bearing
21112	Offset of sensor signal, negative - axial bearing
21121	Increased gain of sensors - axial bearing
21122	Reduced gain of sensors - axial bearing
21211	Increased gain of controller - axial bearing
21212	Reduced gain of controller - axial bearing
21221	Increased setpoint of controller - axial bearing
21222	Reduced setpoint of controller - axial bearing
21311	Offset of control signal, positive - axial bearing
21312	Offset of control signal, negative - axial bearing
21321	Increased gain of control signal - axial bearing
21322	Reduced gain of control signal - axial bearing
21411	Offset of bias current, positive - axial bearing
21412	Offset of bias current, negative - axial bearing
21511	Offset of positive axis bearing current, positive - axial bearing
21512	Offset of positive axis bearing current, negative - axial bearing
21521	Offset of negative axis bearing current, positive - axial bearing
21522	Offset of negative axis bearing current, negative - axial bearing
22111	Offset of sensor signal, positive - radial bearing 1 X axis
22112	Offset of sensor signal, negative - radial bearing 1 X axis
22121	Increased gain of sensors - radial bearing 1 X axis
22122	Reduced gain of sensors - radial bearing 1 X axis
22131	Offset of sensor signal, positive - radial bearing 1 Y axis
22132	Offset of sensor signal, negative - radial bearing 1 Y axis
22141	Increased gain of sensors - radial bearing 1 Y axis
22142	Reduced gain of sensors - radial bearing 1 Y axis
22211	Increased gain of controller- radial bearing 1 X axis
22212	Reduced gain of controller - radial bearing 1 X axis
22221	Increased setpoint of controller - radial bearing 1 X axis
22222	Reduced setpoint of controller - radial bearing 1 X axis
22231	Increased gain of controller- radial bearing 1 Y axis
22232	Reduced gain of controller - radial bearing 1 Y axis
22241	Increased setpoint of controller - radial bearing 1 Y axis
22242	Reduced setpoint of controller - radial bearing 1 Y axis
22311	Offset of control signal, positive - radial bearing 1 X axis
22312	Offset of control signal, negative -radial bearing 1 X axis
22321	Increased gain of control signal - radial bearing 1 X axis
22322	Reduced gain of control signal - radial bearing 1 X axis
22331	Offset of control signal, positive - radial bearing 1 Y axis
22332	Offset of control signal, negative - radial bearing 1 Y axis
22341	Increased gain of control signal - radial bearing 1 Y axis

22342	Reduced gain of control signal - radial bearing 1 Y axis
22411	Offset of bias current, positive - radial bearing 1 X axis
22412	Offset of bias current, negative - radial bearing 1 X axis
22421	Offset of bias current, positive - radial bearing 1 Y axis
22422	Offset of bias current, negative - radial bearing 1 Y axis
22511	Offset of positive axis bearing current, positive - radial bearing 1 X axis
22512	Offset of positive axis bearing current, negative - radial bearing 1 X axis
22521	Offset of negative axis bearing current, positive - radial bearing 1 X axis
22522	Offset of negative axis bearing current, negative - radial bearing 1 X axis
22531	Offset of positive axis bearing current, positive - radial bearing 1 Y axis
22532	Offset of positive axis bearing current, negative - radial bearing 1 Y axis
22541	Offset of negative axis bearing current, positive - radial bearing 1 Y axis
22542	Offset of negative axis bearing current, negative - radial bearing 1 Y axis
23111	Offset of sensor signal, positive - radial bearing 2 X axis
23112	Offset of sensor signal, negative- radial bearing 2 X axis
23121	Increased gain of sensors - radial bearing 2 X axis
23122	Reduced gain of sensors - radial bearing 2 X axis
23131	Offset of sensor signal, positive - radial bearing 2 Y axis
23132	Offset of sensor signal, negative - radial bearing 2 Y axis
23141	Increased gain of sensors - radial bearing 2 Y axis
23142	Reduced gain of sensors - radial bearing 2 Y axis
23211	Increased gain of controller- radial bearing 2 X axis
23212	Reduced gain of controller - radial bearing 2 X axis
23221	Increased setpoint of controller - radial bearing 2 X axis
23222	Reduced setpoint of controller - radial bearing 2 X axis
23231	Increased gain of controller- radial bearing 2 Y axis
23232	Reduced gain of controller - radial bearing 2 Y axis
23231	Increased setpoint of controller - radial bearing 2 Y axis
23232	Reduced setpoint of controller - radial bearing 2 Y axis
23311	Offset of control signal, positive - radial bearing 2 X axis
23312	Offset of control signal, negative -radial bearing 2 X axis
23321	Increased gain of control signal - radial bearing 2 X axis
23322	Reduced gain of control signal - radial bearing 2 X axis
23331	Offset of control signal, positive - radial bearing 2 Y axis
23332	Offset of control signal, negative - radial bearing 2 Y axis
23341	Increased gain of control signal - radial bearing 2 Y axis
23342	Reduced gain of control signal - radial bearing 2 Y axis
23411	Offset of bias current, positive -radial bearing 2 X axis
23412	Offset of bias current, negative - radial bearing 2 X axis
23421	Offset of bias current, positive - radial bearing 2 Y axis
23422	Offset of bias current, negative - radial bearing 2 Y axis
23511	Offset of positive axis bearing current, positive - radial bearing 2 X axis
23512	Offset of positive axis bearing current, negative - radial bearing 2 X axis
23521	Offset of negative axis bearing current, positive - radial bearing 2 X axis
23522	Offset of negative axis bearing current, negative - radial bearing 2 X axis

23531	Offset of positive axis bearing current, positive - radial bearing 2 Y axis
23532	Offset of positive axis bearing current, negative - radial bearing 2 Y axis
23541	Offset of negative axis bearing current, positive - radial bearing 2 Y axis
23542	Offset of negative axis bearing current, negative - radial bearing 2 Y axis

Table 48 – List of warning IDs, warnings detected from limit flags

Warning code (LMM)	Description
31110	Position of shaft not in normal working range - axial bearing
32110	Position of shaft not in normal working range - radial bearing 1
33110	Position of shaft not in normal working range - radial bearing 2
34110	Rotation speed too low

Appendix E – MFLP

Figure 40 – MFLP in test laboratory

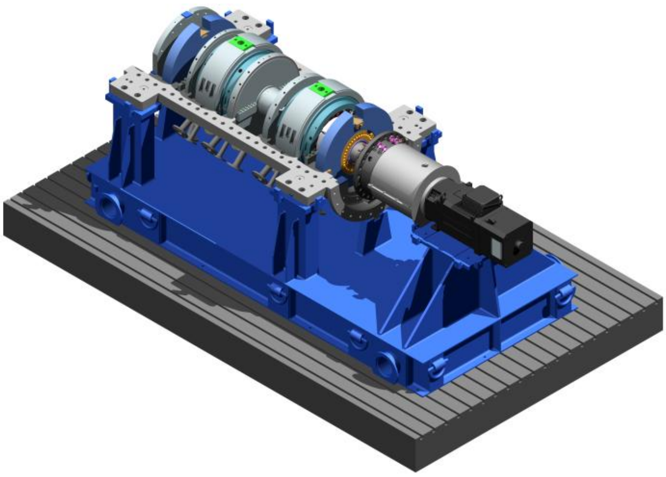

Figure 39 – MFLP view 1

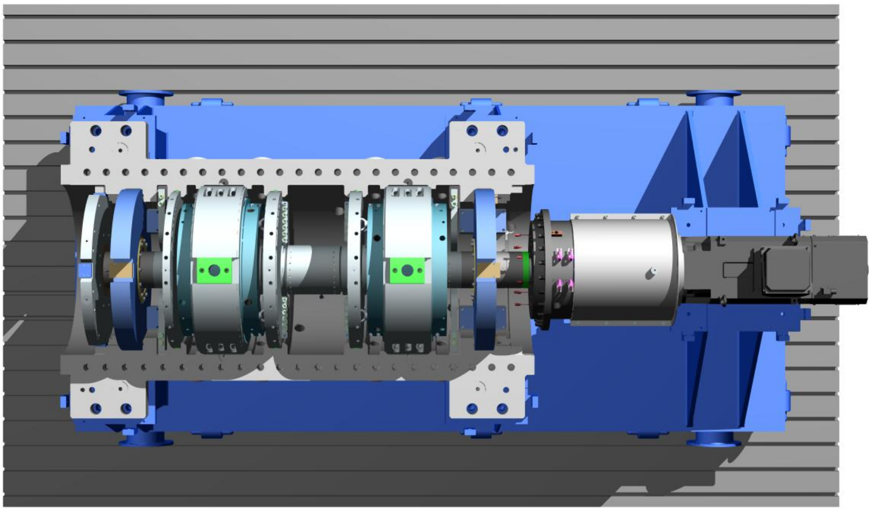

Figure 38 – MFLP view 2

Appendix F – CD contents

1. **MaglapDiagnosticModul.zip** – diagnostic program project + executable file (MaglapDiagnosticModul\bin\Debug\MaglapDiagnosticModul.exe)
2. **AMBVisu1.zip** – android application project
3. **Diagnostic_Modul.pdf** – This thesis in pdf file
4. **AMB_config.ini –** configuration file for diagnostic program (includes extra lines for server side)