Testing the High Speed Shaft of a Yarn Spinning System with a Magnetic Bearing Test Device

Andreas J. Pröll [a], Jiří Sloupenský[b], Peter Dirnberger [c], Wolfgang Amrhein [a]

[a] Institute for Electrical Drives and Power Electronics, Johannes Kepler University Linz, Altenbergerstrasse 69, 4040 Linz, Austria, www.eal.jku.at, andreas.proell@jku.at
[b] Rieter CZ s.r.o., Moravská 519, 562 01 Ústí nad Orlicí, Czech Republic, www.rieter.com
[c] Linz Center of Mechatronics GmbH, Altenbergerstrasse 69, 4040 Linz, Austria, www.lcm.at

***Abstract* - This article describes the possibility and advantages of testing the high speed shaft of yarn spinning regarding its balancing and magnetic behavior by the help of magnetic bearings. The device under investigation is part of a high speed drive which contains magnetic bearings as well.**

I. INTRODUCTION

A. General Information

Small power drives with high rotational speed, low bearing friction, long operating life and low maintenance costs are often requested in industry. A magnetic supported shaft seems especially suitable for yarn spinning applications as its contact-free operation offers low friction and high life-time. Despite many advantages provided by a levitating rotor, its disadvantages lie in the realization complexity and, as a consequence, in their relatively high costs. For mass production the price pressure from the market requires cheap components and fast testing methods.

B. Open End Spinning Technology

Rotor spinning is one of the progressive technologies in the production of textile yarn. Its dynamic development started in 1967, when the rotor spinning technology was tightened up to the commercial stage in the former Czechoslovakia and the machine BD 200 was started to be produced. The productivity of textile machinery working with this technology is primarily determined by the spinning rotors, which are inserted in the machine. The resulting yarn is forming by twist a bundle of the fibres in the rotating part. In order to achieve the desired yarn strength, a minimum value of twist must be guaranteed per yarn length. The achievable production speed of the rotor spinning machine is therefore given by the relationship

$$V = \frac{n}{Z} \tag{1}$$

where V is the production speed in m/min, Z is the number of twists per meter of yarn and n is the rotor speed in rpm. To achieve productivity (production speed) of about hundred meters per minute, rotor speeds in the range of ten-thousands rpm have to be realized. The bearings of the shaft of the spinning rotor have been recognized as one of the key problems of this technology. The requirements are high durability in continuous operation with an acceptable price. The first rotor spinning machines were equipped with double-row ball bearings, which could be brought close to 100 krpm (100,000 rpm). The next step was to drive the spinning rotor by an indirect drive by using rolling discs, which made it possible to operate at a speed of around 150 krpm. The negative factors are considerable energy losses and limited lifetime of exposed parts.

For these reasons, alternatives are needed to ensure high rotor speeds with less power consumption and significantly longer service life. The use of active magnetic bearings is very promising, but a number of partial problems have to be solved. One of them is reported in the following.

II. MOTIVATION OF INVESTIGATION

A. General Comment

The investigated system in this paper is capable to reach speeds up to 200 krpm and, therefore, the implementation of magnetic bearings is one of very few possibilities, to achieve high live times in these yarn spinning applications. However, magnetically supported shafts need to hold strict tolerances for proper operation. To verify the standards and full functionality, a test system including magnetic bearings is proposed. By this test setup the significant mechanical dimensions as well as the magnetic behaviour are checked in one test cycle. Thus, the time for testing the shaft is minimized.

B. Rotor Description

The shaft can be divided into the following areas (Figure 1):

- Radial & axial bearings – areas for magnetic flux
- Drive – motor magnet included
- Exchangeable technology part – rotor coupling

During magnetization and manufacturing of the shaft several tolerances might occur, that lead to problems when commissioning the system. Based on the design of the shaft, quality characteristics can be defined, which guarantee the proper operation:

- Center of mass - limited unbalance
- Magnetization of motor magnet - dipole moment
- Magnetic tolerance - homogeneity and direction of magnetic field

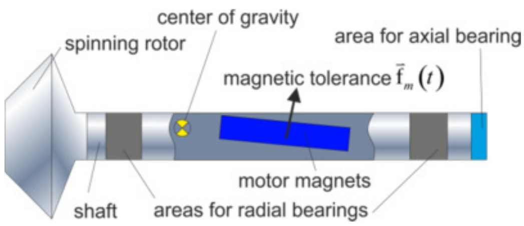

Figure 1: Shaft featuring unbalance and magnetic misalignment of the motor magnet

III. Description of the Test System

A. Design

The shaft is supported by two active magnetic radial bearings and one active magnetic axial bearing.

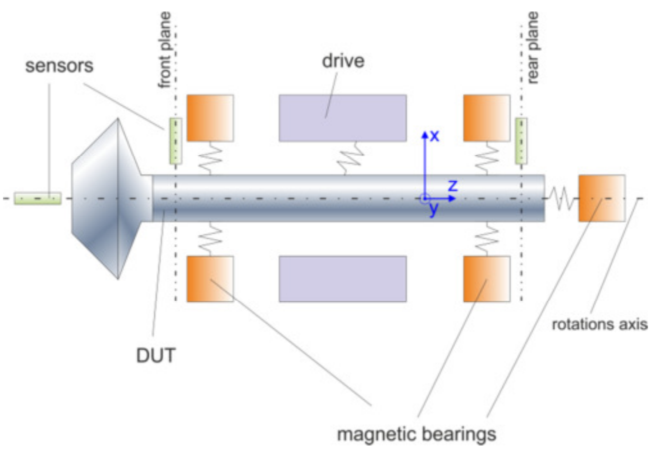

Figure 2: Shaft (device under test) in the test setup featuring magnetic bearings, sensors and a drive. Front and rear planes are defined for position analysis.

B. Bearings and Sensors

Position sensors are used for position control of the magnetic bearings and at the same time for analysis of the position orbit. In the front and in the rear plane positions in x- and y-direction are measured by eddy-current sensors. In addition, the axial direction of the shaft is observed with another eddy-current sensor, which is used to control the thrust bearing. The design of all bearings have been chosen in such way, that the iron losses are negligible compared to the power losses of the drive and first and foremost the power dissipation due to air friction. That means, that the shaft is not braked significantly by the bearings.

C. Bearing Control

The x- and y-axis of the front and the rear bearings have their own independent control circuit. Eddy-current sensors detect the position in each axis. The position signal is filtered by a noise reduction filter and a connectible and speed-dependent notch filter. The PD-position controller calculates the set point for the bearing current and the overlaid current control finds a minimal a position featuring minimal copper losses.

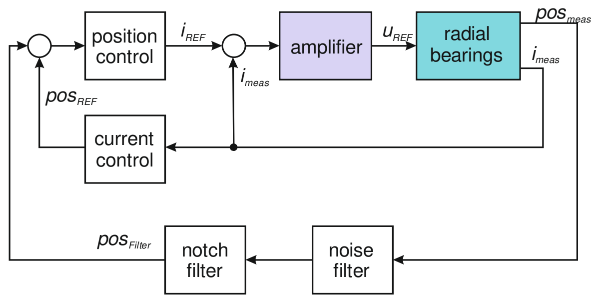

Figure 3: Control scheme of one axis

D. Drive

The drive was built up as a permanent magnet synchronous machine. A three phase winding system in the stator and the shaft magnet provides the torque generation to speed up the shaft for different test modes. The magnet of the shaft must feature the right magnetic properties and the right placement in axial direction to guarantee proper performance. Furthermore, a misaligned magnet might interact with the stator iron, which leads to additional radial and axial forces. The stiffness in axial direction is stabilizing while the radial direction is destabilizing the shaft. Thus, not only drive parameter can be changed by a misalignment of the magnet, also the stability of the bearings has to be considered, because of the destabilizing forces of the motor magnet.

IV. Principles of Testing

A. Points of Operation

The test system approves the most important quality points of the shaft and detects production faults. Therefore, the shaft runs at different rotor speeds and evaluates the properties of the shaft. There are basically four speed levels:

- Operation with very low speed (1krpm)
- Operation with middle speed level (30krpm)
- Acceleration window (40 to 90 krpm)
- Operation with high speed level (100 krpm)

B. Rotor Dynamics

The general equation of motion is given by

$$\mathbf{M}\ddot{\boldsymbol{q}} + (\mathbf{D}+\mathbf{G})\dot{\boldsymbol{q}} + \mathbf{K}\boldsymbol{q} = \mathbf{f}(t) \qquad (2)$$

with system matrices: mass matrix $\mathbf{M}$, the damping matrix

$\mathbf{D}$, the gyroscopic matrix $\mathbf{G}$ and the stiffness matrix $\mathbf{K}$ [1][2], as well as the generalized coordinate vector $\boldsymbol{q}$. The excitation vector on the right-hand side can be divided in two major parts for the investigated system [1]:

Force vibrations due unbalance with

$$\mathbf{f}_u(\mathrm{t}) \sim \Omega^2 \cos(\Omega\,\mathrm{t}) \tag{3}$$

and force vibrations due to magnetic tolerance with

$$\mathbf{f}_m(\mathrm{t}) \sim \hat{F}\cos(\Omega\,\mathrm{t})\,. \tag{4}$$

As a consequence of the small stiffness of the magnetic bearings significant force disturbances generate significant position orbits of the shaft. In Figure 4 the measured orbits are shown during speed up to 30 krpm. Small speeds Ω (at the beginning of acceleration in Figure 4) represent the subcritical area, where magnetic tolerances have an important influence (equation (4)). After rigid body resonances the supercritical area is shown, which represents the orbit due unbalance (equation (3)). Resonances and gyroscopic effects are not investigated in this paper. Based on these considerations, limits for the orbits in both areas can be defined to qualify the behaviour of the shaft in operation.

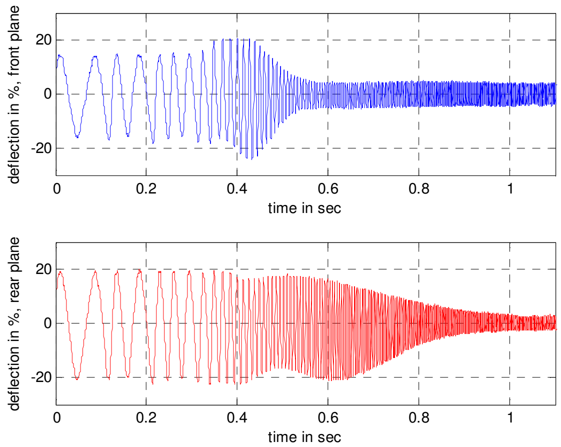

Figure 4: Measured shaft deflections in two planes during speed up to 30krpm

C. *Magnetization of the Motor Magnet*

The torque is created from the stator magnetic flux Φ_h, which is generated by the rotor permanent magnet. The inductance voltage u_{ind} at defined speed in idle state can give information about the magnetization.

$$\underline{u_{ind}} = j\omega\underline{\Phi_h} \tag{5}$$

However, the remanence flux density of rare earth magnets depends on the temperature. Therefore, to validate the magnetization, also the actual temperature must be tracked, when the voltage is recorded.

Another way to prove the proper magnetization is a run-up test with controlled phase currents. In general, the torque is proportional to the phase current, when armature reaction is negligible. When the shafts moment of inertia J_p and the mean breaking torque $\overline{M_{stat}}$ in a defined speed window

$$\Delta\omega = \omega_2 - \omega_1 \tag{6}$$

are known, the torque can be estimated by measurement of the time difference Δt by

$$M_{shaft} = J_p \frac{\Delta\omega}{\Delta t} + \overline{M_{stat}}(\omega_2, \omega_1) \tag{7}$$

D. *Axial Forces*

A deflected axial position of the motor magnet in the shaft generates an axial force due to reluctance forces. An additional influence of the motor current has to be identified. However, the axial forces depend mainly on the following points

- Axial position and direction tolerance of motor magnet
- Magnetization of axial bearing magnet in the shaft
- Aerodynamic forces

So monitoring the thrust bearing control gives information of all these additional axial forces.

V. MEASUREMENTS AND RESULTS

A. *Signals*

For the evaluation of the radial gyroscopic forces, position signals in two axis (x and y) and 2 planes (front and rear) were recorded during the tests in sub- and supercritical speeds. 100% of the deflection of position signals means, that the shaft will touch the backup bearings.

The orbit radii were calculated as a mean value of the sensor signals in x and y direction for 2 periods in the front and in the rear plane. In the subcritical speed area are the angles of the two orbits in phase (Figure 5). After passing some resonance frequency the orbit in rotational speed will overlap whirling, caused by gyroscopic effects. For evaluation of unbalance only the orbit in rotation speed will be considered.

B. *Test Objects*

30 shafts were tested with this test procedure and their evaluation will show in the next sections. These shafts come from different production batches, but have the same dimensions. The goal is to sort out the parts which have too much tolerance and are not useable for yarn spinning.

C. *Identification of Motor Magnet Tolerances*

A shaft driven below all natural frequencies of the rigid body featuring an asymmetric placed motor magnet (Figure 1) will generate circumferential forces in phase with the rotating speed. Due to the PD-behavior of the radial bearing control, a displacement in force direction will result as the control features not integrational part. This position displacement moves with the rotational speed and gives information of the magnetic unbalance. For small speeds (e.g. until 2000 rpm) with respect to the natural frequencies, the orbit remains constant in both planes. Thus, large magnetic tolerance leads to significant orbits, and the rotor can touch the backup bearings, what has to be avoided.

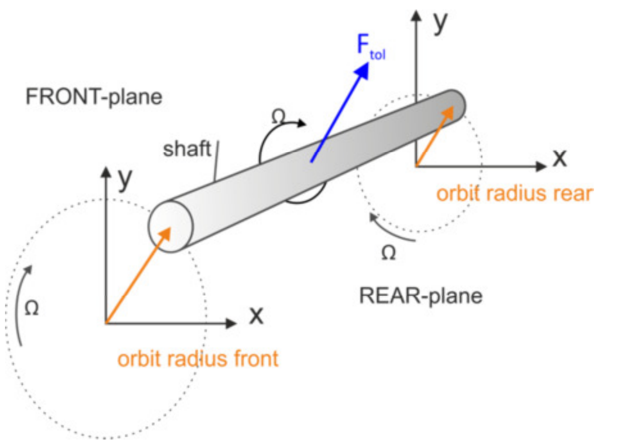

Figure 5: Schematic illustration of a subcritical rotating shaft in eccentric axis with calculated orbit radius for two planes

Interestingly, the measurements of the shafts showed, that shafts without magnetic tolerances (very precise parts) rotate with a certain orbit, too. This is explained by the interaction of the flux leakage of the homopolar magnetic bearings with the diametric magnetized rotor magnet. In Figure 6 the separated flux of the bearings and of the motor magnet are shown. Of course, the bearing flux through the motor area is very small in comparison to the motor flux, but nevertheless, not negligible. A superposition of both fields generates forces to the shaft depending on the rotation angle equal to an eccentric motor magnet. This influence was determined and considered in the evaluation of the measurement results.

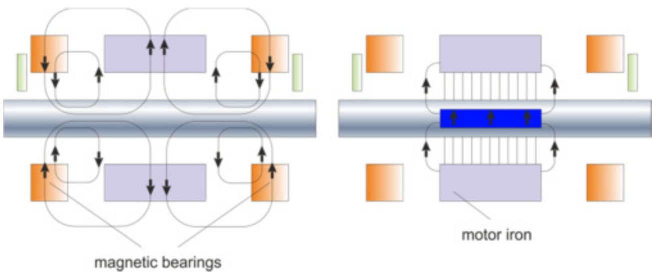

Figure 6: Left: static flux leakage of homopolar biased magnetic bearings in the air-gap and through the stator iron; Right: flux of motor magnet through air-gap and stator iron

Figure 7 shows the determined values of the front and the rear orbits of different 30 shafts at 1 krpm. The defined limit should delineate the parts with too much tolerance in the rotor magnet. For example shaft number "3" and "17" have much bigger deflections as all others. This can lead to problems at lift-off and acceleration. Especially, when a heavy spinning rotor is mounted, the shaft tends to touch the backup bearings during rotation what has to be avoided. Shaft "3" was analysed in detail to find out the reason of this behavior. After cutting up the shaft a measureable eccentric assembled motor magnet was identified.

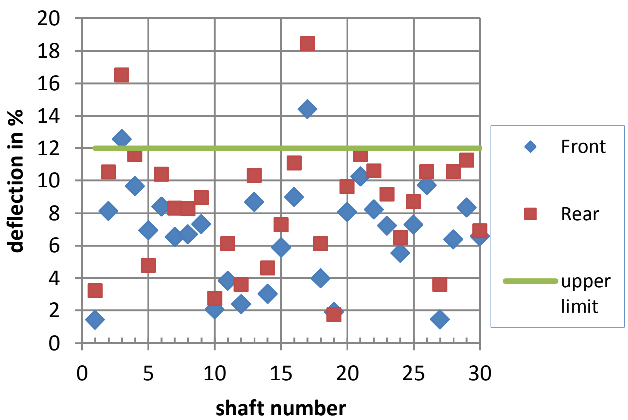

Figure 7: Measurement result of subcritical orbit radius in front and rear plane

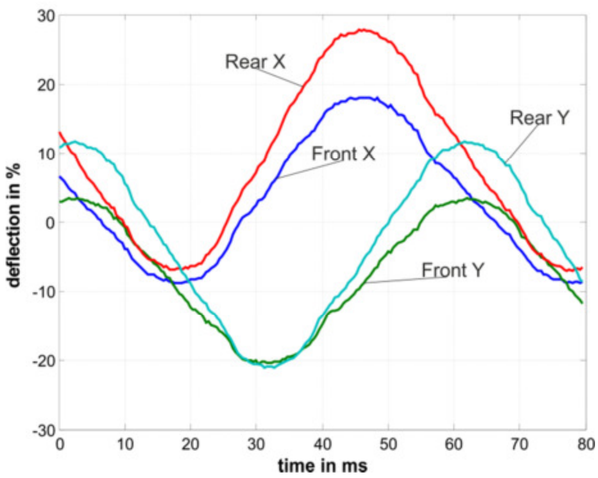

Figure 8: Measurement of radial position signals of shaft "3" at subcritical speed of 1000 rpm

On the other hand some shafts had a very less orbit (e.g. shaft "1" or "19"), meaning that the magnetic tolerances compensate the influence of the bearing flux, which was described in the previous section with the help of Figure 6. Hence, these shafts will run quite good in subcritical speed area, although the magnetic field of the shaft is not symmetric.

D. Measurement of the Shaft Unbalacne

At supercritical speed, far beyond the resonances of the rigid body, the shaft is rotating around its axis of inertia, which is known as "self-centering-principle" [1][3]. Thus, the rotor deflections, which are measured on the outer shape of the shaft, depend on the unbalance and additional gyroscopic whirling effects [5]. The position signal in the frequency range of the rotational speed is defined as supercritical orbit and gives information about the unbalanced mass of the shaft.

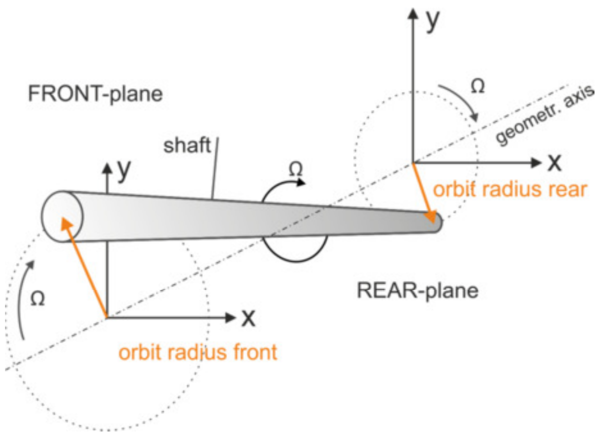

Figure 9: Schematic illustration of a supercritical rotation of shaft with unbalance around self-centering axis

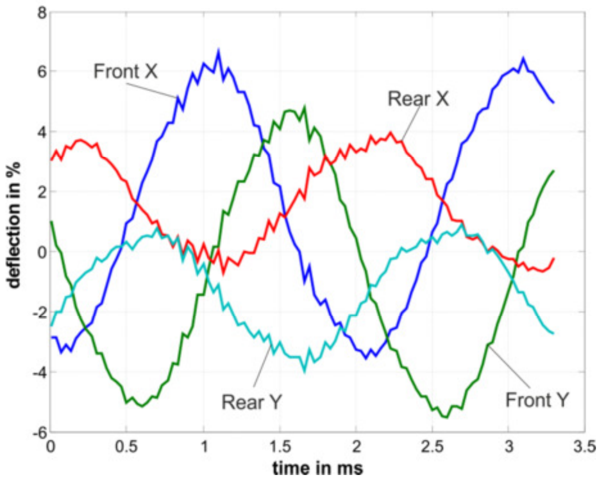

Figure 10: Measurement of radial positions signal at supercritical speed at 30 krpm of shaft “13”

A balancing procedure is not proposed and should not be necessary for these shafts and thus, the exact parameters of the unbalances are not important. However, maximal deflections must not exceed defined limits, caused by an asymmetric shaft. The speeds during yarn production are approximately 2 octaves higher than the rigid body resonance. Thus, to pass the natural frequencies without touching the backup bearings has to be ensured by enough acceleration and damping. A detailed investigation of the frequency response is not conducted in this work as it is not necessary for this testing application. A good quality of the yarn spinning requires bounded radial vibrations of the technological spinning rotor at the static production speed.

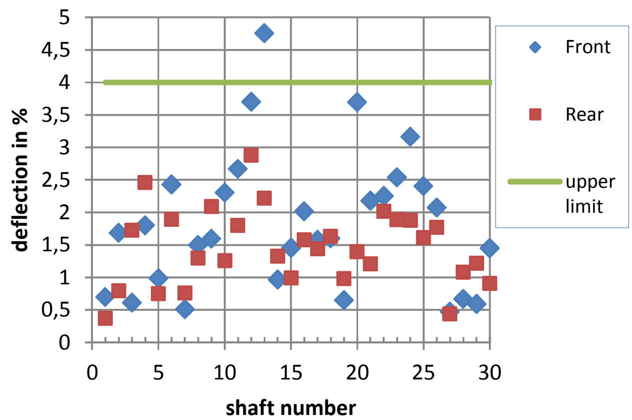

Figure 11: Orbits of the shafts at supercritical speed

In Figure 11 only one shaft (“13”) exceeds the maximal defined limit for permissible unbalance. In comparison to the classification of applications corresponding balance quality grades of ISO 1940 [6], the measured eccentricities are much higher, due the very high rotational speed. However, for this application of yarn spinning a proper orbit radius of the rotor does not reduce the quality of production, significantly.

E. Axial Forces

Axial forces are recognized by the mean (steady state) current of the axial bearing. Due to flux linkage and saturation effect the force-current relation of this bearing is not linear. But a defined limit for the maximal control current can be found, which represent for a maximal and acceptable axial force. Of course, the tolerances of the axial bearing have to be identified before and considered in the measurement.

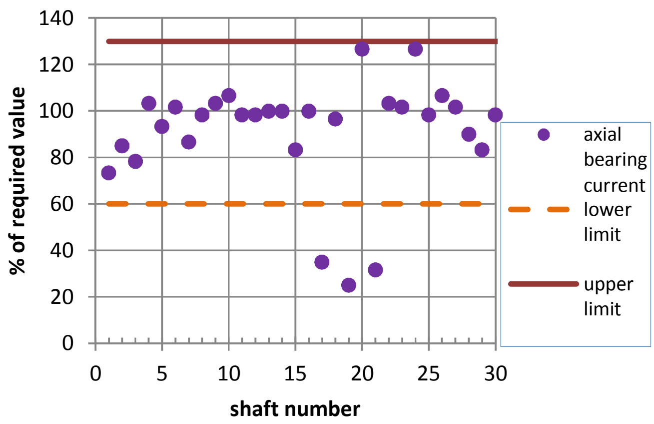

Figure 12: Measured current of the axial bearing; upper limit: too much losses, lower limit: too less performance

The axial bearing magnets of the shafts “17”, “19” and “21” have not the correct magnetization. This is clearly visible in Figure 12, because the measured axial bearing current is very low. 100% of the axial current is defined as the expected current of the axial bearing. In this measurement two shafts have a significant higher bearing current near the defined limit. To identify the reason for this, deeper investigations are needed.

F. Magnetization and EMF

As already mentioned in section IV.C, the polarization of the magnet can be checked by the inducted voltage and by the acceleration time. This gives a certain redundancy and additional reliability, concerning unknown parasitic effects, e.g. temperature rise, during the measurement. Limit values for run-up acceleration and the induced voltage can be identified to fulfil the specification of the drive.

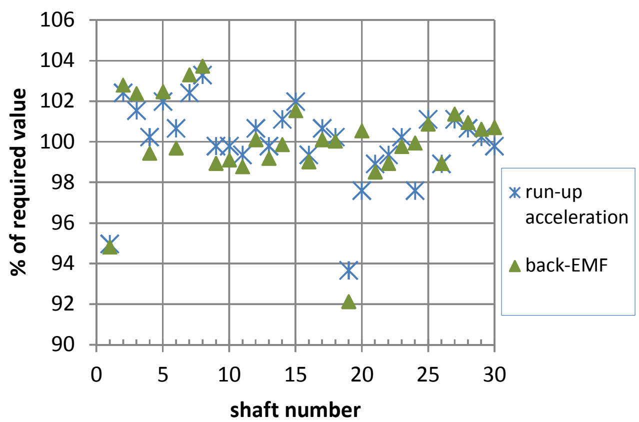

Figure 13: Measured induced voltage (back-EMF) at stable speed and average run-up acceleration

The measurements in Figure 13 show a good correlation of average run-up acceleration from 40 to 90 krpm and the induced voltage (back-EMF) measured at static speed of 100 krpm. 100% in this measurement is defined as the expected value. The magnetization of shaft number "19" is too small obviously and marked as a "failed part". Shaft "1" has only 95% of the nominal performance that means, that the torque is approximately 5% lower at the same phase current compared to a shaft with 100% back EMF.

VI. Analysis of Measurements

In summary, five of 30 tested shafts do not pass the defined criteria.

shafts, no.	*fault description*
3, 17	too much magn. tolerance – position and magnetization of rotormagnet
13	too much unbalance
17, 19, 21	magnet for axial bearing wrong - demagnetization
19	too less EMF – inadequate magnetization of motor magnet

VII. Conclusion

This paper discusses a test procedure for yarn spinning shafts in series production. Some of the most important parameters, like unbalance and magnetization fluctuation of the rotor magnet can be checked quite easy with the described test system. Furthermore, additional parameters that influence the bearing-forces are also observed. Measurements of 30 shafts were conducted. Some shafts exceeding the production tolerances or featuring damaged magnets were detected successfully. A test run is performed in a time period of some seconds per shaft and needs a bearing system similar to the application itself. Hence, the usability in a mass production line for random test and fault monitoring is clearly shown.

Acknowledgement

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