Landing Tests with a 6300rpm, 9t AMB Rotor in Rolling Element Back-up Bearings

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***Abstract*— This article describes a systematic approach to qualify backup bearings for very large rotors levitated by active magnetic bearings (AMB). The approach comprises dynamic simulations of the landing events prior to the testing with good prediction quality as part of the safety concept. The approach was applied for the backup bearing qualification of a 9t rotor with a rotational speed up to 6420rpm. The results of the landing tests are shown and compared with the simulation results.**

I. INTRODUCTION

A. *Background*

As previously described in [1], Siemens AG has developed a new active magnetic bearing system based on SINAMICS standard drive technology. As part of the development, back-up bearings based on ball bearing technology have been developed in cooperation with Schaeffler Technologies GmbH & Co. KG (Schaeffler). It is widely agreed in the AMB community that a rotor in ball back-up bearings is less likely to develop a backward whirl than a rotor in sleeve bearings due to more advantageous friction conditions. To qualify the back-up bearings for large high-speed applications with high rotor weights, several speed-graded landing tests [2] or [3] with an electric 6300rpm synchronous double-end drive prototype motor are performed. To our knowledge, using ball back-up bearing technology in a motor application of this size with a 9t rotor, a maximum speed of 6300rpm and a backup bearing inner diameter of 360mm is new.

B. *Objectives of the landing test program*

With a specific customer application in mind, the landing test qualification program is to provide evidence that the back-up bearings fulfill the customer, i.e. that they are capable of

- withstanding a minimum of 3 drops from full speed (6300 rpm) with a braking time of 13 seconds realized with the converter actively braking the motor
- handling one full rundown with a braking time as long as 100 seconds without damage to the motor, while back-up bearing damage is allowed; the prolonged braking time simulates a malfunction of the braking system, in which case the process forces of the application define the braking duration

If the condition of the backup bearings still permits it, after the qualification program has been completed, the setup will be used for additional experiments to gain experience on special malfunctions in the magnetic bearing system, such as the failure of only one magnetic bearing axis.

C. *Overview of the preparation and execution of the tests*

Due to the novelty of the application, considerable efforts were made during the development of the bearings as well as the preparation and execution of the tests in order to ensure safety and to make the tests and thus the qualification of the product a success:

- Extensive simulation studies during development of the back-up bearings [4] performed by Schaeffler, including FEM and transient landing simulations.
- Landing tests in a smaller application with a 1.3t rotor with higher rotor speed (12,700rpm) in order to gain experience with comparable circumferential bearing speeds, which are an important parameter in a ball-bearing application.
- Definition of a qualification program delivering a certain level of confidence that the back-up bearing design will fulfill the customer requirements with a sufficient safety margin.
- Transient landing simulations of the complete qualification program as preparation for the landing tests, using both a simulation environment developed by Schaeffler [4] and a simulation environment developed by Siemens AG [5].
- Safety concept.
- Extensive landing test procedure with well-defined checks after a landing as well as stop/go criteria for execution of the next landing test.

The various steps are explained in more detail in the following.

II. SYSTEM SETUP

A. *Prototype Motor Setup*

The prototype double-end drive motor has been designed for a maximum speed of 6300rpm and a trip speed of 6420rpm (exceeding the trip speed results in an automatic braking command for the converter). The motor comprises two radial magnetic bearings, see Figure 1. The two radial back-up bearings are installed on the outboard side of the magnetic bearings, see Figure 2. The motor is not equipped with an axial bearing, since axial bearings are part of the driven machine. However, axial bump stops are integrated into the radial back-up bearings.

Figure 1. Radial magnetic bearing of the prototype motor from the SIMOTICS Active Magnetic Bearing series.

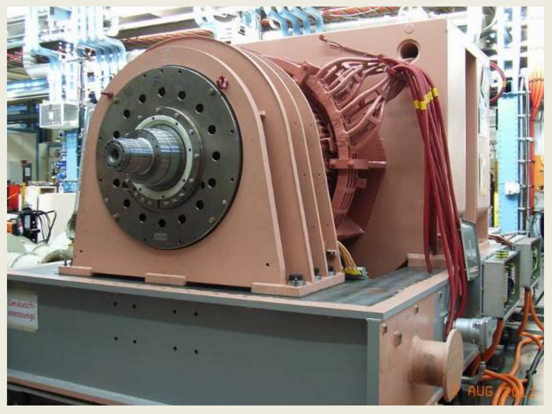

Figure 2. Radial back-up bearing of the prototype motor.

The back-up bearings are double-raceway ball bearings with ceramic balls and an elastic element [4]. The back-up bearing gap for this large application is 500µm to account for thermal expansion and assembly tolerances. The back-up bearing gap is about 25% of the AMB air gap, and significantly smaller than the air gap of the motor stator, which prevents, under all circumstances, rotor-stator contact at any points other than the back-up bearings.

In order to simulate the future on-site system configuration as closely as possible during the landing tests, the rotor is held in its axial position by the original EDE (exciter drive end) coupling, which is attached to a spindle-like device with two pre-stressed pairs of ball bearings, see Figure 3. The expected radial deviation of the rotor during the landing tests can be tolerated by the EDE coupling. At the DE side, the actual DE (drive end) coupling is simulated using a dummy coupling to obtain identical rotor dynamics.

Figure 3. Motor setup during the landing tests with the original coupling and coupling spacer mounted on the EDE side to provide axial guidance.

The motor is located in a room with reinforced walls for safety reasons. Due to the restricted space in this room, the motor cover and cooler were removed for the landing tests.

The motor is driven by a converter so that the motor can be braked from top speed within less than 20sec. The rotor position in the magnetic bearing, the bearing current, the bearing voltage and the rotor speed are monitored by the SIMOTICS active magnetic bearing system. A trip signal is generated if certain threshold values are exceeded indicating e.g., that the rotor has left a position window around the setpoint position. In turn, a trip causes the converter to perform an emergency stop and brake the motor.

A drop switch deactivates the enable signals of the AMB axes, causing the rotor to land in the back-up bearings. Depending on the parameterization of the drives, all or specific bearing axes can be deactivated. Reactivating the enable signals with the drop switch allows the rotor to be relevitated, also see section IV.B.

The motor can be braked by the converter at any time by pressing an emergency stop button.

B. *Back-up bearing instrumentation*

The radial magnetic bearing position sensors are mounted close to the radial back-up bearing. This means that their signals can be used as a measure for the rotor position in the back-up bearings.

Since the back-up bearings are based on ball bearing technology, it can be expected that the temperatures in the backup bearings during run-down remain low. This is verified by measuring outer ring- and inner ring temperatures of one back-up bearing using probes in direct contact (outer ring) or optical temperature probes (inner ring).

III. LANDING TEST PROGRAM

A. *Preliminary landing tests*

To establish an initial proof of concept that the ball back-up bearing design will be able to cope with the high circumferential bearing speeds during a landing specific to the target application, landing tests with a 1.3t high speed rotor ([1], [7]) have been performed prior to the tests with the 9t rotor. The extensive test program comprised 60 landing tests with full run-down at different speeds and braking times from speeds of up to 12,700rpm on one set of back-up bearings. After this test program was completed, the bearings were still fit for the purpose. In this way, a circumferential back-up bearing speed of 94% of the target application was achieved. In addition to gaining experience, these tests were performed to develop the safety concept and to write a dynamic simulation software that is able to predict the experimental results of back-up bearing tests.

B. Qualification program

In order to demonstrate the endurance of the back-up bearings and that customer specifications are complied with as listed in section I.B, the test program has been made more stringent compared to customer specifications:

- API 417 Annex 4F for expander compressors on magnetic bearings suggests in section F7.7 a test for new back-up bearings, which includes a 3s delevitation into the back-up bearings at maximum speed followed by a relevitation. This test simulates a situation that is as close as possible to a real run-down situation in the field with respect to temperature rise, see Note 2 for section F7.7. Instead of this suggestion, braked run-downs to zero speed have been scheduled, which are even closer to the actual field conditions.
- The braking time from trip speed is increased to 19sec compared to the customer requirement of 13sec – with the exception of the 100sec landing
- The braking curve is programmed to be linear. In the future field application the process load of the driven machines will result in a braking torque proportional to the square of speed, i.e. the initial slope in the speed decrease will be steeper than for a linear braking curve. In the field, the rotor will thus leave the critical high speed range faster than in the conservative linear approximation

Furthermore, the number of landings has been increased compared to what the customer specified:

- A landing at 1200rpm, 2400rpm, 3600rpm, 4800rpm and 6000rpm each preceding the landings at trip speed, see also the section about safety features IV.E.
- 5 landings at the trip speed of 6420rpm and 19sec braking time with deactivation of all 4 bearing axes instead of the required 3 landings
- 1 landing at the trip speed of 6420rpm and 100sec braking time

C. Additional system testing after the qualification program

If the state of the back-up bearings permits it, after completion of the qualification program, the following optional additional tests have been scheduled. The purpose of these tests is to gain experience with the behavior of the rotor in conjunction with the closed-loop controlled bearing system in exceptional circumstances, which in principle could occur in the AMB system setup:

- deactivation of a DE and an EDE bearing axis, i.e. two bearing axes at trip speed
- deactivation of a DE bearing axis at trip speed
- deactivation of an EDE bearing axis at trip speed

IV. SAFETY CONCEPT AND TEST EXECUTION

Besides a loss of rotor integrity during the landing test, a backward whirl [6] is the most critical system behavior that might occur, since the bearing forces that occur during a backward whirl can severely damage the back-up bearing system. Thus, measures need to be taken to minimize the risk that the above events occur. The following main measures have been identified based on a risk assessment.

A. Design phase and test preparation

- Experimental modal analyses of the rotor and calibration of the simulation environment
- Validation that the weakest rotor parts, such as the end winding covers and coupling bolts between exciter and main shaft, are able to cope with the simulated forces that occur when a rotor drops
- Verification calculation that the connection between motor base frame and foundation as well as the connection between motor stator and base frame will withstand even the worst case scenario that a rotor locks
- Extensive simulation studies for drops with various initial conditions, worst case unbalance situations and worst case eccentricities of the back-up bearing sleeves on the rotor to gain confidence that the design is robust with respect to a backward whirl, i.e. that a backward whirl does not have to be expected

B. Test system setup

- The drop switch can be remotely actuated at a safe distance away from the motor in axial direction
- The rotor behavior can be monitored at the remote location using the HMI system of the SIMOTICS Active Magnetic Bearings
- The drop switch allows the rotor to be relevitated in the event of a potentially critical situation
- The emergency brake button allows the rotor to be braked in the event of a potentially critical situation
- Online monitoring of the inner ring temperature to allow relevitation, should the bearing temperature-gradient deviate from what is expected
- UPS allowing levitation of the rotor for more than 30min, should the power supply in the plant fail; the power supply must be restored within this time so that the motor can be actively braked

C. Initial checks

- Check that the automatic braking of the rotor is initiated reliably and instantly when the rotor reaches a trip level, in particular the position trip level
- Check that the converter can brake the rotor from trip speed (6420rpm) in less than 19s
- Check the functionality of the UPS, emergency brake button and inner ring temperature measurement

D. Initial tests

- Smoothly place the rotor into the back-up bearing; check the effect on the radial rotor position and calibrate the simulation environment

- Landing at 0 rpm and calibration of simulation environment to rotor behavior
- Ensure that the deviation of the delevitated rotor from the back-up bearing center is within expected values (elasticity effects)

E. *Test execution*

- Start data recording
- The rotor is accelerated up to the appropriate landing speed; to reduce the probability of a back-up bearing failure at high speed due to a design flaw, the landings are graded according to speed (1200rpm, 2400rpm, 3600rpm, 4800rpm, 6000rpm, 6420 rpm)
- The drop switch is activated and the rotor falls into the back-up bearings
- As soon as the rotor position reaches the trip level, a trip is automatically generated by the AMB system and the converter brakes the rotor to a standstill

F. *Test evaluation*

- Comparison between the results of the dynamic simulation and experiment in terms of orbits, rotor deflection in the bearings, and whirling tendency; since dynamic simulations are time consuming, all landings of the test program have been simulated in advance; to account for uncertainty in the unbalance situation, the simulations have been executed for an in-phase (static) and out-of-phase (dynamic) unbalance situation; nevertheless, an exact reproduction of measured trajectories is not possible because of the complexity and the number of parameters that influence the initial conditions in a particular landing (e.g. rotor position when the drop switch is actuated); it is therefore more reasonable to compare the major trends of a landing that are independent of the details of the initial contact; should the prediction quality of these trends deviate from expectation, the parameterization of the simulation environment needs to be improved based on the measurement results; otherwise, the test program does not have to be delayed by on-site simulation runs
- Visual inspection of the back-up bearing assembly, of the rolling elements and of the raceways using an endoscope
- Verification that the rotor deviation from the center position of the back-up bearing is small enough and within what can be expected, i.e. that the bearing deflection is within expected tolerances, and that there is no chance of the rotor coming into contact with the stator
- Verification that the result of a clearance check does not show any increase in the bearing air gap, which might result from plastic deformation; for the bearing clearance check the rotor is pushed gradually against the back-up bearing's inner ring in the radial direction at equally spaced angular intervals with an automated procedure; the bearing/rotor contact is detected by changes in the measured current; the coordinates of the bearing/rotor contact points are then used to estimate an average clearance
- Proof by dynamic simulation that the next landing test at higher speed will not result in unwanted dynamics.

If the outcome of all above points is positive, the next landing of the landing test program can be prepared and executed.

V. TEST AND SIMULATION RESULTS

A. *Qualification program*

The eleven landings of the qualification program including the 100sec landing were successfully completed and without any unexpected effects. The rotor exhibited good behavior at all times. The prediction quality of the simulation runs performed prior to the tests was good enough regarding the key features so that the test program could be continued without any need for simulation parameter calibration.

Selected measurement results are shown in the following, together with simulation runs performed by Siemens AG. More details about the simulation environment as well as further simulation and measurement results can be found in [5]. Simulation results from the simulation environment of the Schaeffler company are described in [4].

Measurement results of the first three landings at 6420rpm with 19sec are shown in Figure 4. From the measurement results it can be concluded that the deviation of the rotor from the setpoint position during the landing due to elasticity of the back-up bearing is significantly smaller than the active magnetic bearing air gap of about 2mm. Thus, there is no risk that the rotor comes into contact with the AMB stator. It can also be noted, that the rotor behaved in a similar fashion during the three landings regarding the area in the back-up bearing in which the rotor moves as well as in the number of larger loops in vertical direction.

The corresponding simulation result for the landing at 6420rpm with 19sec is shown in Figure 5. Although the horizontal movement of the rotor in the back-up bearing is wider, key features such as the bouncing height have been correctly predicted. Also, as in reality, the bouncing height at the DE-side is higher than at the EDE-side. Most importantly, neither in the simulation nor in the measurement, was there any indication of undesirable dynamics, such as a forward or a backward whirl.

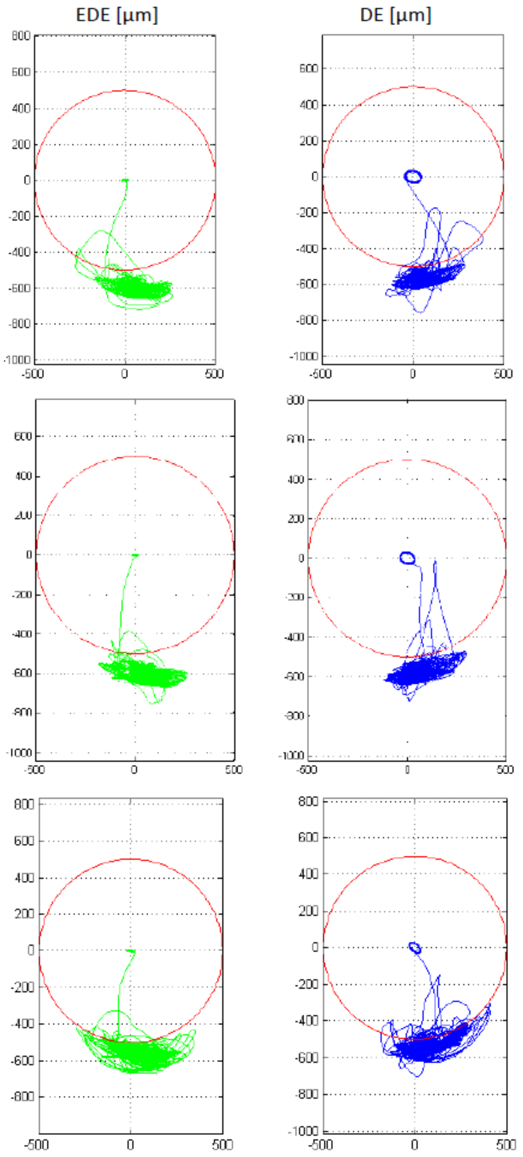

Figure 4. Measurement results of the first three landing tests at 6420rpm with a braking time of 19sec.

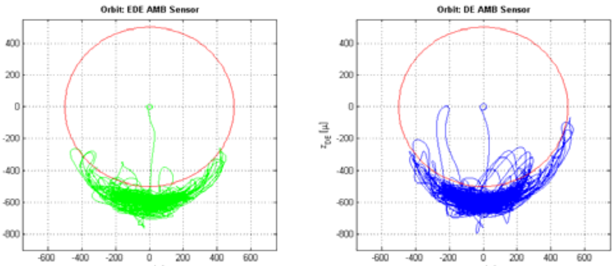

Figure 5. Simulation result of the 6420rpm landing with a braking time of 19sec.

An additional example is the landing test at 6000rpm, which is shown in Figure 6. as measurement and in Figure 7. as simulation result. Also here, the bouncing height has been correctly predicted by the simulation, however, the movement of the rotor in the horizontal direction is larger in simulation than in reality. However, since the measured movement in horizontal direction is more confined – and thus even less critical with respect to the development of unwanted dynamics than in the conservative simulation – it was not necessary to tune the simulation model.

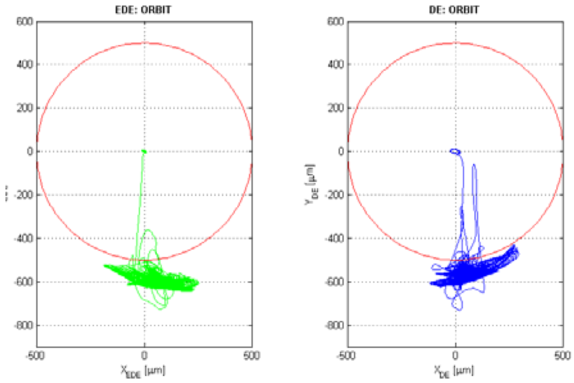

Figure 6. Measurement results of the landing tests at 6000rpm.

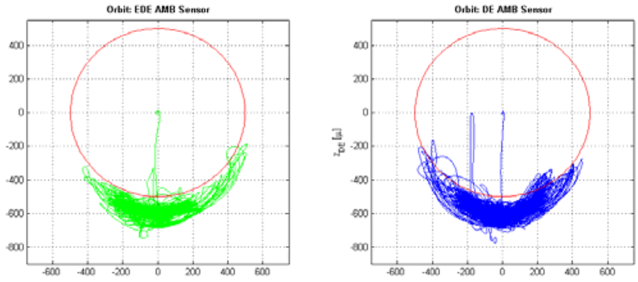

Figure 7. Simulation result of the landing tests at 6000rpm.

Figure 8. shows the result of a clearance check after the 100sec landing at the end of the qualification program at the DE and EDE back-up bearing. The bearing air gap (~550µm), given by the radius in the above diagrams, did not change with respect to the result of the clearance checks before and during the landing program, i.e. there are no indications that the bearing geometry changed.

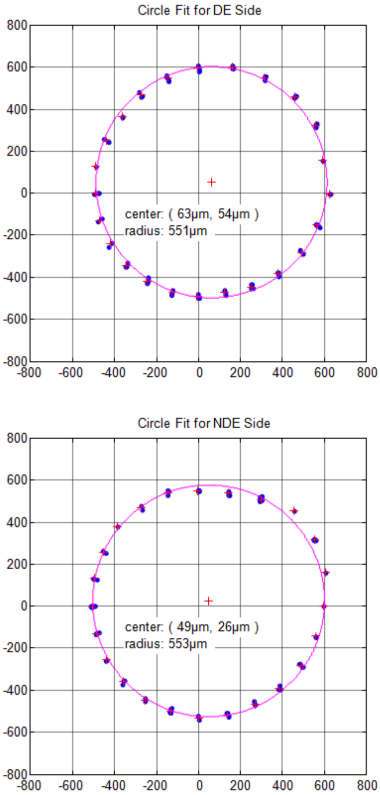

Figure 8. Result of the clearance check at the DE and EDE bearing after the 100sec landing at the end of the qualification program.

The endoscopic examinations of the bearings after the individual drops did not show any problematical amount of wear patterns at the balls or the bearing rings; see the example in Figure 9.

Figure 9. Optical endoscopic examination of the bearings after the 100sec drop at different regions of the bearing did not show any worrying amount of wear.

The temperature measurement at the bearing's inner ring indicated a typical temperature rise of 3 K during the 19sec drops and a temperature rise of 16 K during the 100sec drop. These temperature rises lie significantly below the worst case design values.

B. *Gaining further experience*

In order to learn more about the behavior of the closed-loop controlled system in case of single-axis drops, e.g. due to an AMB amplifier failure, landing tests in individual bearing axes have been performed. As an example, a landing into only one axis of the EDE bearing is shown in Figure 10. It can be seen that the system response is well behaved, and that the rotor comes to a safe standstill with all but one axis in levitation.

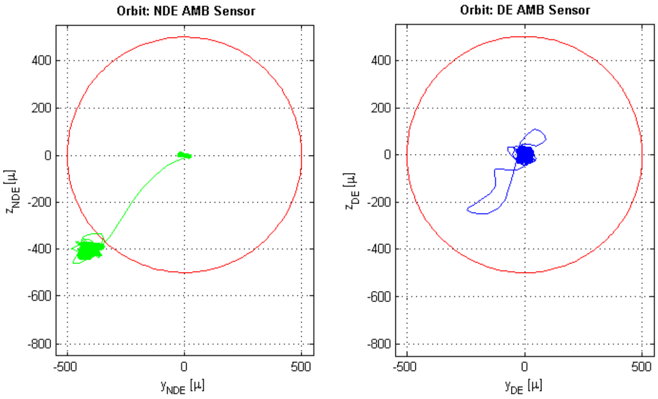

Figure 10. Simulation result of a single axis landing with only one axis of the EDE bearing having been deactivated.

C. *Discussion of the results*

The presented theoretical and experimental results demonstrate the durability of ball back-up bearings in very large machine applications. The credibility of the methodology comes from the comparison between theoretical and experimental data as well as from structural integrity checks, which were performed on the bearings after each drop. The objective of this test strategy is twofold: i) to show that ball bearings can withstand the load levels associated with challenging landing tests, and ii) to validate the simulation methodology through the correlation between experimental and simulated results. The latter in particular provides confidence in the predicted results of such simulations for development and design purposes. Testing to bearing failure would have been very informative, however, very expensive and unnecessary with respect to ensuring that customer specifications are complied with. Thus, the confidence gained from the test program described above is seen as a good compromise.

VI. CONCLUSION

The landing test concept described in this article can be used as a guideline to back-up bearing qualification. It allowed the systematic and safe execution of landing tests on a very large AMB machine with a maximum landing speed of 6420rpm and a rotor weight of 9t. The dynamic simulation runs of the landing events performed prior to each landing test as part of the safety concept predicted the rotor behavior measured during the landing with good quality. Accordingly, there was no indication of unwanted dynamics such as backward or forward whirl during the tests. The landing program carried out with a total of 11 landings (5 at 6420rpm and 19sec braking time, one at 6420rpm and 100sec braking time) proves the feasibility of ball back-up bearings for the prototype machine described. To our knowledge, the use of ball back-up bearings for machines of this size and speed is unique.

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