Simulation and Experimental Validation of a 9t AMB Rotor Landing in Rolling Element Back-up Bearings

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Abstract—Backup Bearings (BuB) must be designed to withstand the shock loads which occur during impacts with heavy and/or high-speed rotors. Both experimental testing and transient dynamic simulation are necessary for the study of BuB performance. This paper presents the transient dynamic simulation methodology developed within SIEMENS for the study of full-scale rotor landings in rolling element BuBs. The developed models were validated with a substantial landing program led and performed by SIEMENS, whose objective was to qualify the safe operation of hybrid rolling element BuBs for an industrial application utilizing an AMB-levitated 9t supercritical motor. The paper describes the BuB model, summarizes the simulation results and offers a comparison with experimental measurements from the aforementioned successful landing tests program.

I. INTRODUCTION

The implementation of Active Magnetic Bearing (AMB) technology for the support and operation of large rotating machinery has been gaining ground in recent years due to the advantages it introduces in comparison to conventional fluid-film bearing technology, such as frictionless operation and the flexibility to implement active control concepts. A primary concern for rotating machinery OEMs and their customers is the continuously safe operation of equipment under all operating conditions. BuBs are a necessary and central component for the safety of AMB-levitated rotor systems. In the event of an AMB shut-down or failure, the BuBs will support the rotating parts during the landing, absorb the impact loads and will allow the rotor to coast down to standstill.

For large rotor AMB-machines the use of dry friction BuBs has been the preferred practice in the industry. It is common knowledge that friction-BuBs promote the contact conditions necessary to result in the backward whirling of rotors. High rotor vibration amplitudes due to fully developed backward whirl-type rotor motion can cause severe damage or even destroy the rotating machinery. The kinematics of rolling element bearings significantly reduce the possibility of backward whirling during landings. However, technical literature on the subject cites cases where rotating machines can exhibit backward whirl type rotor behavior during landing in rolling element BuBs as well [1].

This paper presents the methodology developed by SIEMENS to simulate numerically the transient dynamic behavior of rotors during landings. The developed numerical framework is based on a detailed kinematic description of the rotor and bearing component movements and of their interactions during a landing event. The methodology has been validated with measurements from an extensive landing program which was performed by SIEMENS Dynamowerk in Berlin to qualify a rolling element BuB-solution for a large 9t motor drive application [2]. To our knowledge, the utilized BuBs are the largest to have been reported for this type of application.

The BuBs are based on a novel cage-less design developed by Schaeffler Technologies GmbH & Co. KG in collaboration with SIEMENS. They consist of two rows of ceramic ball rolling elements, a common inner ring with two separate outer rings, and a housing with asymmetric compliance [3].

The objective of the BuB qualification program was to demonstrate the safety of transient operation, not only for the particular project-specific application, but also to prove that rolling element BuBs can fully withstand the landing of heavy rotating machines without promoting backward whirling. The presented simulation method was an integral part of the safety concept for the 9t rotor landing qualification program. Landing simulations were performed prior to the landing experiments to predict the occurrence of possible mechanical failures during a landing.

The simulation results presented in this paper aim to demonstrate the agreement achieved between experimental measurements and simulation predictions and to show that the existing numerical framework can be used to make reliable predictions for the rotor-dynamic behavior and the mechanical performance of rotating machinery in the future.

II. 9T-ROTOR LANDING TESTS ON ROLLING-ELEMENT BACK-UP BEARINGS: EXPERIMENTS & SIMULATION

A. *Modeling of Transient Rotor Dynamics*

The simulations are performed with proprietary software developed within SIEMENS for transient dynamic calculations.

The rotor modeling is based on the finite element method, and serves as input information for the SIEMENS code. The rotor is discretized with an appropriate number of cylindrical beam elements with the commercial FEM software MADYN, and the developed model is calibrated against a free-free rotor modal test. After modal fitting, the FE description is converted to a standard dynamic system state-space formulation for numerical integration. The stiffness, mass and damping matrices of the tuned model are exported for further use as input to SIEMENS' transient dynamics solver. External system disturbances enter the system of linear algebraic equations through the force vector. Such excitations can be unbalance forces, gravity loads, process loads, braking torques or AMB centering forces. Forces due to rotor-BuB contact interactions enter the system of equations in the same manner through the force vector.

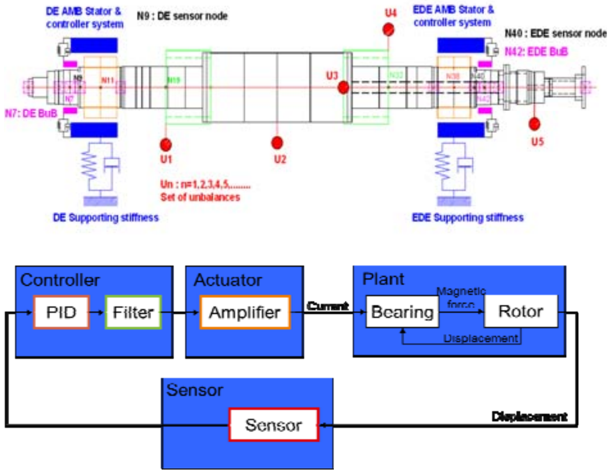

Figure 1 Complete mechatronic simulation model.

The key feature of the Siemens code is the full 3D kinematic modeling of the complete BuB system. The kinematics of each BuB component and the interactions between neighboring bodies are described in detail for all six degrees of freedom (DOFs) with the relevant equations of motion (see Figure 2).

The contact forces which develop during landing between the rotor shaft and the BuB inner ring are based on Hertzian contact theory considering the stiffness properties of the contacting materials and the geometries of the contacting surfaces. Similarly, Hertzian contact laws are used for the calculation of contact forces, which arise from the eventual ball-to-ball contact (due to the cage-less design) as well as for the continuous ball to inner and outer ring contacts. Friction forces are derived from the normal component of the corresponding normal contact forces using static/sliding friction coefficients, which depend on the properties of the contacting materials, the differential speed and the roughness of the surfaces involved.

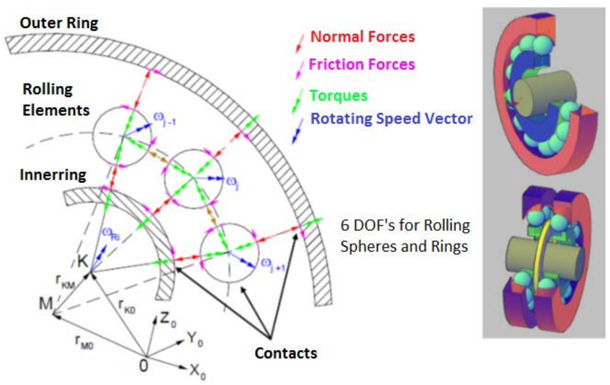

Figure 2 2D schematic simplification of the Siemens BuB model.

B. Experimental Landing Tests

A number of landings have been performed with the 9t prototype machine [2]. For safety purposes it was decided that rotor testing should not be initiated with the trip speed of 6420rpm before the system landing behavior was studied at lower landing speeds.

Five preliminary landings took place with gradually increased initial speeds in order to observe any unwanted or unexpected tendencies in the system's dynamic behavior. The rotor was dropped from 1200rpm, 2400rpm, 3600rpm, 4800rpm and 6000rpm prior to the intended qualification drops. Each landing was triggered by simultaneously deactivating both supporting radial AMBs. The rotor was decelerated to zero speed with a constant (speed-independent) electromagnetic braking torque, which caused the rotor speed to decrease linearly. The braking torque was selected to decelerate the rotor from 6420rpm speed to rest in 19sec. The same torque was used in each landing test, thus test duration was proportional to the initial drop speed.

After the successful completion of the lower speed landings, the BuBs were qualified for drops at the trip level speed. The rotor was dropped five times from the bearing's center at 6420rpm speed with a 19sec braking time, again triggered by simultaneous deactivation of all four AMB axes.

Landing from the trip speed with braking only due to aerodynamic resistance (and in absence of any electromechanical braking torque as the case would be in compressor or turbine applications) was simulated with a landing test in which the rotor speed decreased from 6420rpm to zero over 100sec. A lower braking torque was applied in this case to achieve the desired deceleration.

Finally, the prototype's rotor-dynamic behavior was also evaluated for different patterns of AMB failure with additional drop tests from the trip speed. Drop tests were performed with:

- one AMB axis deactivated on both AMBs, (only the x- or only the y-axis active at both AMBs), and
- one AMB axis deactivated at one of the AMBs.

In the industrial application being considered, the rotor is utilized as a double-end drive, and its axial movement on the drive train is constrained by the axial AMB installed on the rotating machine coupled to the rotor's EDE (exciter drive end). The couplings used are compliant in their lateral direction to eliminate radial interactions between coupled drive train components. For the landing tests, the couplings attached to the rotor ends are replaced by dummy weights of appropriate weight and inertial moments. To ensure that the dropped 9t rotor would not axially shift during the landing program, it was axially coupled to a rolling element ball bearing, which restrained axial motion but allowed rotation at all speeds. The coupling used during the tests was radially compliant and did not influence the lateral movements of the rotor during landing and coast-down. In simulations, this condition was applied by eliminating the DOF corresponding to the rotor's longitudinal translation.

C. Results: Test and Numerical Simulation

This section presents a representative set of landing test results recorded during qualification program together with the corresponding simulations. As mentioned in the previous section, several drops with a gradually increasing initial speed were performed. The results presented here are from tests with the most challenging landing conditions for the rotor and the BuBs (speed and duration). Two of the five 19sec landings from 6420rpm speed are presented along with the 100sec landing test from the same speed.

For completeness in presenting the system's physical response and the code's predictive capacity, additional results from tests with inherently different initial conditions are also presented: a landing from an intermediate initial speed (3600rpm), a landing from the maximum speed (6420rpm) with single-axis AMB deactivation at the DE and EDE, and a maximum speed drop with one AMB deactivated (at the DE).

The simulated behavior for each of the experiments presented here is compared to the experimental measurements to validate performance of the SIEMENS code.

- Numerical Modeling Preliminaries

The rotor's FE model is based on the available design geometry and material properties. Thus, all mass distributions and moments of inertia are accurately transferred into the model. Further, the rotor model was calibrated with data from modal analysis (hammer) tests to match the measured mode shapes and modal frequencies. Modal damping of 0.5% was assumed as realistic for all simulations.

The AMB controller parameters and magnetic field properties used for the simulations are those of the prototype machine.

To ensure modeling accuracy, the stiffness and damping properties of the BuB pedestal model were calibrated using rotor vibration data recorded by the AMB sensors in tests where the rotor was dropped from different positions within the BuB clearance with zero rotational speed. In all simulations, gravity was acting in the vertical axis, and was applied equally to the rotor, the AMB housing (stator) and to all components of the BuB; namely, the rolling elements, the inner- and outer rings, and the bearing housing.

In contrast to the aforementioned quantities – which are either known or can be directly determined from existing measurements – the friction coefficients, as well as the stiffness and damping values for the contacts between the rotor and the BuB inner ring, as well as between rolling elements, and between rolling elements and bearing raceways can only be estimated. The selected values must be physically reasonable, i.e., based on widely accepted values for contact between metals and/or ceramics, and with rational proportionality to the damping and stiffness values used for the remaining components of the model.

The rotor was balanced prior to the landing tests. However, the exact distribution of the residual unbalance along the rotor was unknown. Thus, for the simulation model, the unbalance weight distribution (location and phase) was varied until an acceptable match was accomplished between simulated and measured orbit amplitudes for rotation inside the AMBs. An in-phase unbalance grade of G1.5 was selected.

Finally, the landing position inside a BuB and the contact conditions during this initial touchdown of the rotor can be a determining factor for the initiation of whirling. Thus, an effort was made in simulations to reproduce not only the measured orbit, but also the rotor's trajectory after the AMBs had been deactivated, such that the initial landing conditions for a particular landing experiment and the corresponding simulation would be as close as possible. This was achieved by matching the position on the orbit at which the bearing was switched off.

Without loss of physical accuracy and as described in the previous section, all simulations were performed with the rotor's longitudinal translation (x-axis translation) fixed and the five remaining DOFs free (y- and z-translation; x-, y-, and z-rotation).

- 19sec landing: 6420rpm initial rotor speed

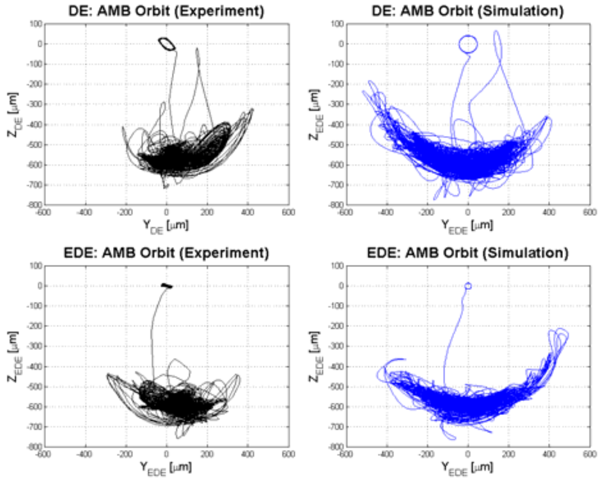

Figure 3 Measured and simulated rotor orbits at the AMB locations. (5th landing from 6420rpm)

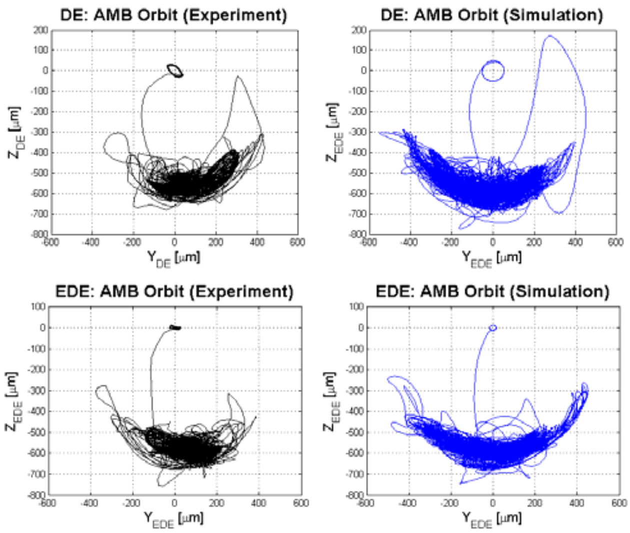

Figure 4 Measured and simulated rotor orbits at the AMB locations. (4th landing from 6420rpm)

The measured orbits for each of the five 19sec braked drops from maximum speed (6420rpm) were practically identical. In addition, for the same drop speed, the similarity in the behavior between the 19sec and 100sec drops is remarkable (when the results are presented in terms of rotating speed). Therefore, it is evident from the measurements that the system's response is highly repeatable and consistent. The orbital characteristics of the rotor as it passes through different critical frequencies during deceleration remain unchanged regardless of the initial drop speed or the duration of the coast-down

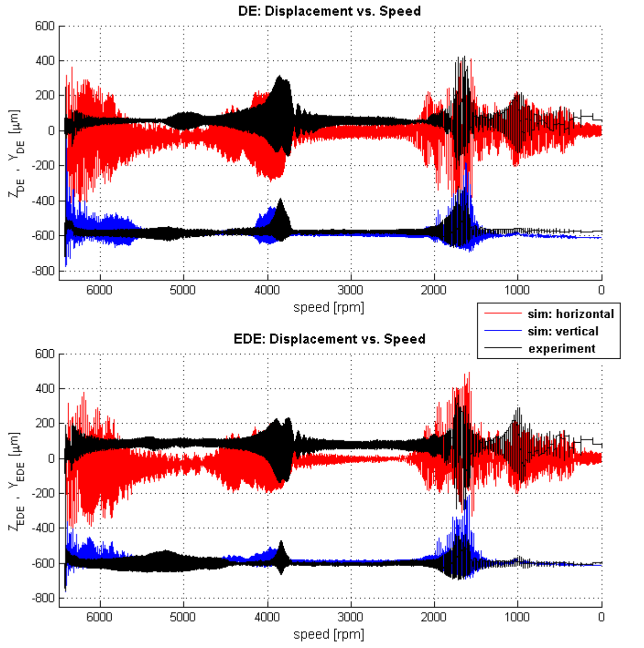

Figure 5 Measured and simulated lateral displacement at AMBs vs. speed. (5th landing from 6420rpm).

- 100sec landing: 6420rpm initial rotor speed

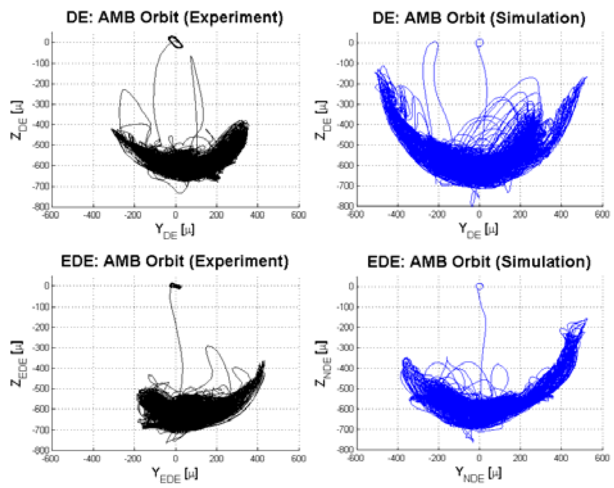

Figure 6 Measured and simulated rotor orbits at the AMBs. (100sec landing from 6420rpm).

The two additional resonances which appear in the 100sec deceleration around 5600rpm and 4800rpm are identified as natural frequencies of the BuB pedestals, which are not excited during the 19sec coast-downs, as the rotor only remains at these critical speeds for a limited time when compared to the 100sec landing scenario.

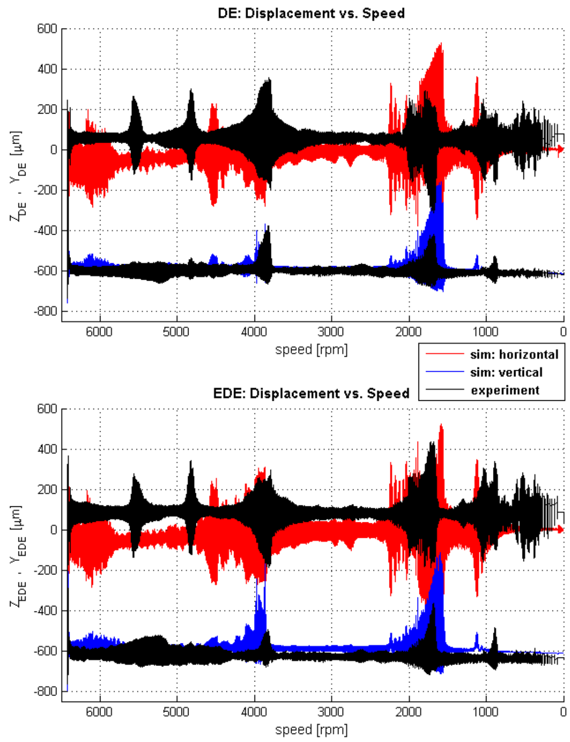

Figure 7 Measured and simulated lateral displacement at AMBs vs. speed. (100sec landing from 6420rpm).

It should be noted that the design feature introduced by Schaeffler Technologies GmbH & Co. KG (see [3]) to add compliance at the lower part of the BuB-housing in an area concentrated at the vicinity of rotor touchdowns has not been accounted for in the model presented here. This feature ``arrests´´ the rotor after a landing and limits its pendulum motion. The discrepancy between the simulated and measured horizontal movement of the rotor (the horizontal component, shown by the red line in Figure 5 , Figure 7 and Figure 9) is attributed to this omission and an improvement is due in this direction.

It should be noted that the measured rotor orbits are not perfectly cyclical during operation in the AMBs, due to asymmetrical properties of the foundation in the testing facility where the landings took place.

Drops from lower speeds exhibited the same characteristics for overlapping speed ranges, indicating that the rotor assumes the same deflection shapes at a given speed. These observations qualified the prototype machine – including the rotor and all bearings – as highly robust, as no alterations or failures were manifested throughout the landing program.

- 12sec landing: 3600rpm initial rotor speed

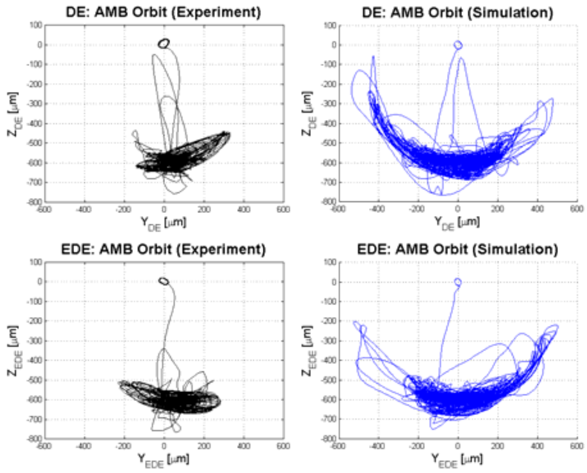

Figure 8 Measured and simulated rotor orbits at the AMBs. (12sec landing from 3600rpm).

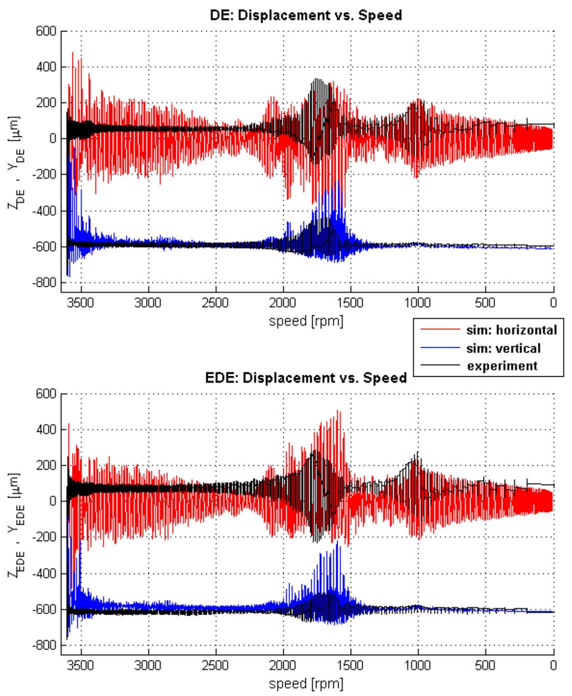

Figure 9 Measured and simulated lateral displacement at AMBs vs. speed (12sec landing from 3600rpm).

- Single AMB single-axis shutdown landing: 6420rpm

Figure 10 presents the measured and simulated orbits for a single axis drop from the trip speed. The x-axis of only the DE AMBs is deactivated. The rotor slides down sideways at the DE without any striking effects. It can be seen that the still fully actively controlled side is disturbed and tends to follow the initial trajectory of the landing side, is however, steered back to the AMB center position. The disturbed orbit inside the fully active AMB is only a result of excitations from the highly contained orbit inside the BuB at the DE.

Figure 11 presents the measured and simulated orbits after deactivation of the x axis at both AMBs. The AMB axes are rotated by 45° to the horizontal. With only the y-axis of the AMBs active, the rotor slides downwards under the influence of gravity, and lands sideways in the BuB at an inclination of 45° (the direction of the deactivated x axis). The tendency of the DE to bounce more after the first touchdown is evident in both measurements and simulations.

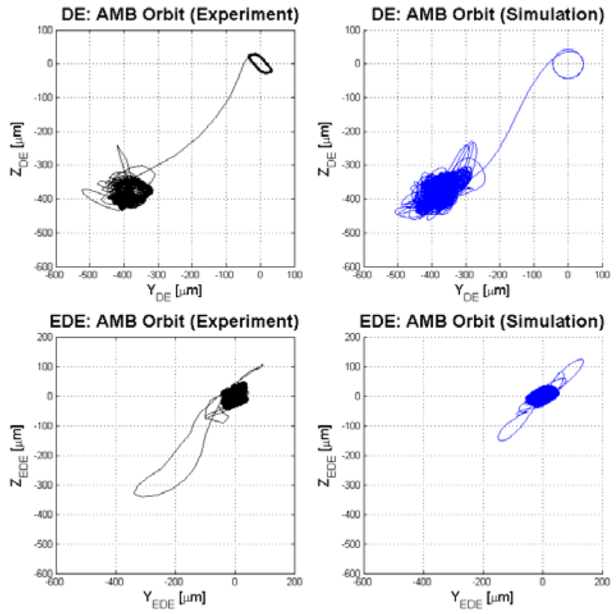

Figure 10 Measured and simulated orbits after deactivation of the X-axis at the DE AMB .

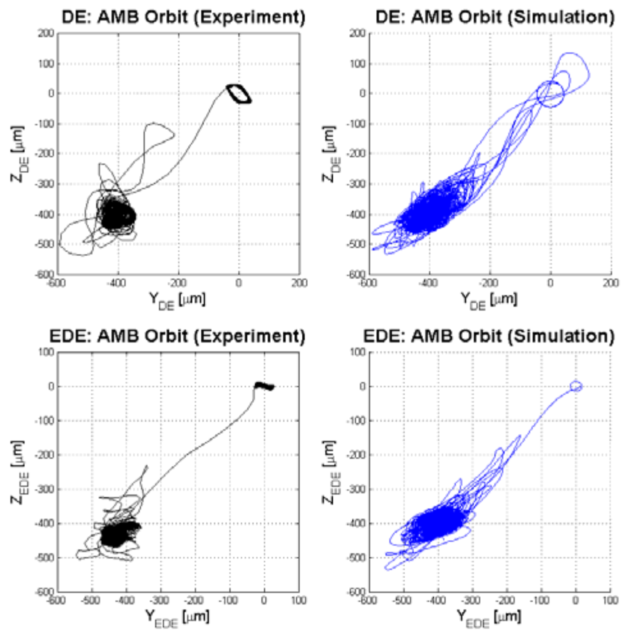

Figure 11 Measured and simulated orbits after deactivation of the X axis at both DE and EDE AMBs.

Effort was again made in the aforementioned simulations to deactivate the AMBs at the appropriate time instance so that the rotor would depart from its circular orbit at the correct position and follow the trajectory observed in the landing tests before touchdown in the BuBs. The quality achieved in the simulated response is visible in the characteristics of the initial transients (e.g., the eight shape in Figure 10).

- Discussion

The software used for transient rotor dynamics within SIEMENS has been validated against the results of the landing experiments. It can be used to predict backup bearing performance in other landing situations, e.g. higher rotor unbalance, without the need for further experiments. Moreover, it allows for design optimization as it permits the numerical monitoring of quantities which otherwise cannot be recorded, but might be essential for analysis. Such quantities can be internal to the BuBs, such as inner ring and rolling element speeds, contact stresses at BuB components, BuB temperature rise due to friction, rotation of components in space or compliant/damping member deformations when the BuB is in use.

Other important quantities are the developing contact forces and the resulting torques acting on the rotor and the BuB inner ring during touch-down and deceleration.

Figure 12 and Figure 13 offer an example of the detail in BuB analysis which can be achieved with the developed software. Such information is crucial for the development of reliable equipment.

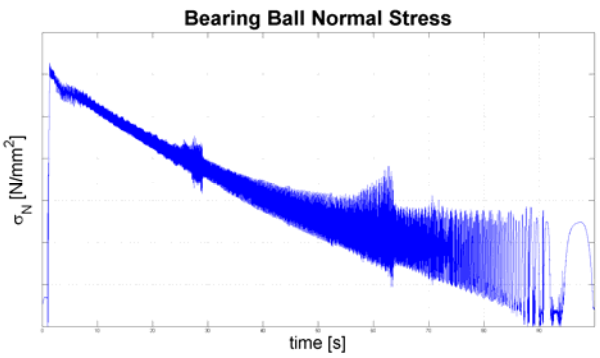

Figure 12 Simulated time evolution of the contact stress on a randomly selected rolling element from the 100sec drop.

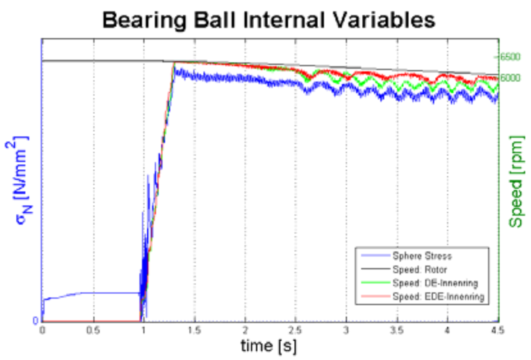

Figure 13 Simulated contact stress on a sphere element and its correlation to inner ring speed directly after rotor touchdown in the BuB. The stress curve is a detailed excerpt from Figure 12 .

III. Conclusions

It has been demonstrated that rolling element bearings can perform as backup bearings for high-speed, heavy rotating machinery. A full-scale demonstration took place at SIEMENS Dynamowerk in Berlin with a 9t heavy rotor system rotating at a speed of 6420rpm. To our knowledge, this has been the most demanding application reported for backup ball bearings.

The performed experimental program included a set of rigorously planned and monitored landing tests, which can serve as a benchmarking quality standard for the qualification of backup bearing concepts which have to satisfy requirements beyond the established experience in the field.

A methodology developed by SIEMENS for transient dynamic simulations was presented. The proprietary software can be used for predictive rotordynamic analysis during emergency landings in BuBs. The code accounts for all bearing subsystems and for their physical interactions with the rotating components. It was validated through several landing experiments and provides a reliable tool for the prediction, analysis and improvement of the performance and reliability of future rotor system designs.

References

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