Experimental Investigations on the Properties and Dynamic Behaviour of a Hybrid Bearing System for Turbo Machines

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Abstract: Within the frame of an international research program that was supported by the European Commission, one subtask was to determine the dynamic behaviour of rotating shafts of turbo machines using a Hybrid Magnetic Bearing Concept (HMBC). This HMBC denotes the combination of Active Magnetic Bearings (AMB) with an additional Permanent Magnetic Bearing (PMB). For the present investigations a permanent magnetic radial shear force bearing was used. Due to their characteristics the conventional active magnetic suspension and the permanent magnetic support affect each other. This mutual action has to be considered at the benefit analysis of a hybrid bearing system.
This contribution outlines the scientific approach of these studies. The overarching objective was to make the results sustainable to use. Therefore validated models will be necessary that are able to recreate the dynamic behaviour of a magnetic suspended rotor with the support of an additional permanent magnetic bearing. The basis of this approach is the application of methods of theoretical and experimental modelling. The validation of the created models was made with reference to experimental tests on the FLP 500 test facility in Zittau, Germany. For the necessary experiments the completely AMB-supported test rig was equipped with an additional permanent magnetic radial bearing.

Keywords: Hybrid Magnetic Bearing Concept, Hybrid Bearing System, Active Magnetic Bearing, Passive Magnetic Bearing, Modelling

Introduction

Intention of a Hybrid Magnetic Bearing Concept. Prior results of research in AMB Technology for heavy turbo machines have shown that the loads occurring while the rotor drops under high rotational speed may damage the Touch Down Bearings (TDB). Experimental research in the late 80s demonstrated that the load could be minimized by centring the rotor of the FLP 500 [1]. Therefore the TDBs could be activated by their whole circumference and achieved a more regular acceleration then.
The combination of AMBs and PMBs is likely to promise many advantages which were investigated in the R&D project. The idea of a permanent support for the centring of the rotor, even in case of an AMB failure, came up on the mentioned results of prior research. A Permanent Magnetic Bearing provides an additional radial guidance of the rotor that may reduce the loads on the TDBs when the AMB support fails [2].
Objectives. The objective of this research and development project was a fundamental research of the potentials of such a hybrid bearing concept. The questions which had to be answered were directly related to the application for heavy turbo machines with vertical shaft orientation. Besides the feasibility of the hybrid magnetic bearing concept itself, the most important problem definitions were:

- Generates the combination of a permanent magnetic radial bearing and active magnetic bearings any useful synergetic effects?
- Can the radial restoring forces of the permanent magnetic bearing be used for centring the rotor in case of AMB-failures?
- Is it possible to reduce the loads that impact the Touch Down Bearings in case of AMB-failures?
- Is the control system of the active magnetic bearings applicable to compensate the instability and missing damping properties that are introduced by the additional permanent magnetic bearing?

Basic Approach to the Investigation on the Properties and Dynamic Behaviour of a Hybrid Magnetic Bearing Concept

Steps. The basic approach of this R&D work was in a first step to design a permanent magnetic radial shear force bearing. The design, construction and manufacturing of the PMB were done in the research centre of Juelich, Germany. This PMB had to be used for experimental tests on the FLP 500, a completely AMB supported test rig of the IPM in Zittau, Germany. The second step was the physical modelling of the HMBC. These models were used for closed simulation calculations, evaluating the dynamic behaviour of the HMBC. The simulation calculations were also used to determine the specifications of the control system due to additional instabilities that are introduced by the PMB. The experiments that were performed at the FLP 500 with the additional PMB had two major objectives – to validate the physical modelling and to determine achievable effects of a HMBC for specified applications.

Design of a Permanent Magnetic Radial Shear Force Bearing. Modern permanent magnets made from NdFeB feature high magnetic stability and make it possible to support permanently heavy loads without fatigue or wear. By taking advantage of field effects at the edges of the magnets it is feasible to design bearings with high stiffness by using only small volumes of such magnet material. The Permanent Magnetic Bearing which has been employed for the present investigation has been particularly optimized for best radial stiffness and designed with respect to easy fabrication and assembling. The primary structure of the rotor- stator magnet configuration can be seen in *Fig. 1*. It is an identical pair of two concentric ring magnets, which serve as rotor and stator bearing part respectively. With the indicated magnetic polarisation and 1mm air gap between both double rings the positive stiffness, which is generated by this elementary bearing configuration for displacements in radial direction, is about 200N/mm.

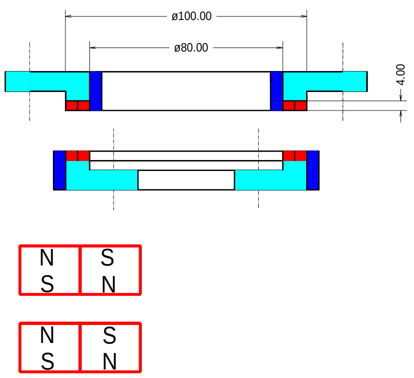

Fig. 1: primary structure of the rotor-stator magnet configuration of the PMB

A stack of 11 such double ring stator magnet units in combination with a stack of 10 corresponding double ring rotor magnets make the functional part of the PMB (*Fig. 2*), which has been set up for present studies. The double ring units are framed in stainless steel collars which produce a nominal gap between rotor and stator magnets of +/-1mm magnet and are enclosed by a steel housing which serves as magnet yoke and closes the permanent magnet circuit.

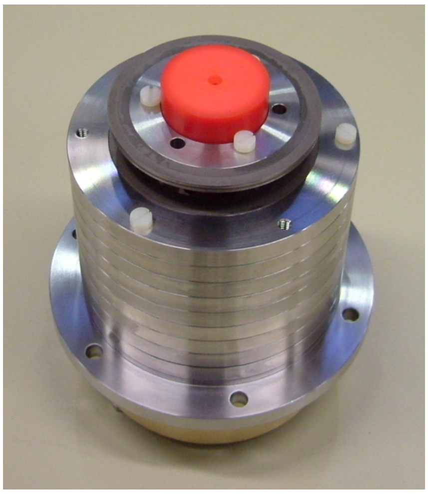

Fig. 2: preassembled ring magnet unit of the PMB

Estimation of the physical parameters of the PMB. The stiffness of the PMB configuration has been calculated by 3D simulation with a Finite-Boundary-Element method (FARADY) and 2D simulation (FEMM). The positive stiffness in radial direction is 3570 N/mm at a negative axial stiffness of -7700 N/mm. These results had been confirmed to be in good agreement with extrapolated values from force versus displacement measurements performed with load cells in a test set-up for a single pair of rotor-stator magnets.
Considering the example of the PMBs forces in axial direction the measured results of the single pair of magnets are plotted in the diagram in *Fig. 3*. The nonlinearity of the single pair of ring magnets become linear stiffness characteristic that is constituted by the differential assembly after multiplying the stack size, demonstrated in *Fig. 4*.

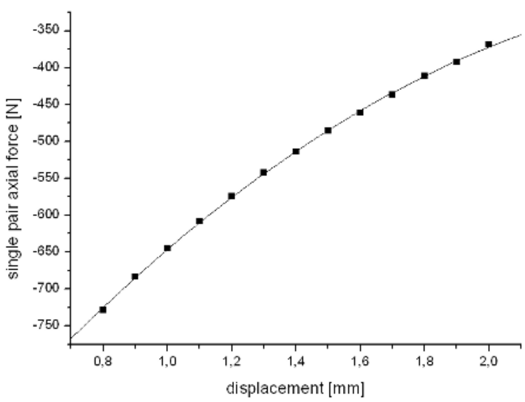

Fig. 3: nonlinear axial stiffness of a single pair of ring magnets

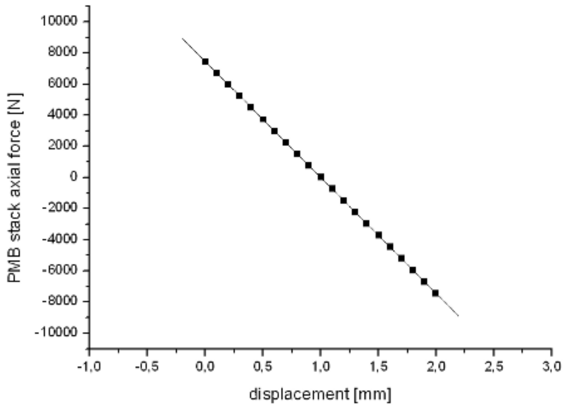

Fig. 4: linear axial stiffness of the whole PMB stack

Extrapolating the experimental determined radial and axial stiffness to the stack size, the radial stiffness of the whole assembly is about 3527 N/mm and for the axial stiffness -7444 N/mm. Both stiffness parameters of the PMB are linear. In radial direction the PMB reacts with a restoring force against any deviation of the rotor from the centre position. In axial direction the PMB works unstable with the effect that a deviation out of the axial centre position will be gained in that direction. The challenge of the active support by the axial AMB is to set and hold the desired rotor position above the centre point of the PMB, as the negative stiffness will work against the rotors dead weight.

Modelling and Model Analysis of the Hybrid Magnetic Bearing Concept. The performance of dynamic simulation calculations with MLDyn provides easy support for testing controller structures and optimizing the controller parameters within the closed loop. Also for preparing the experimental tests at the test rig basic studies of the controller design had to be per-formed in advance by simulation. Those theoretical considerations included not only the behaviour at the working position, but even the functions for start-up and smooth landing control of the shaft. Therefore different sets of controller parameter had to be adjusted. This work was quite essential as the compensation of the additional instabilities – caused by the PMB – were one of the biggest challenges within these studies.

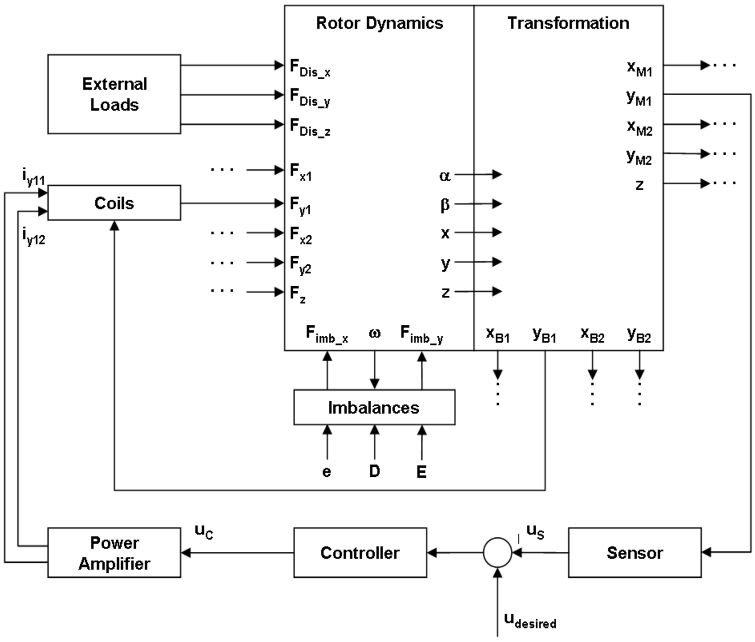

Fig. 5 modular structure of the simulation tool MLDyn

MLDyn is a specific CAE tool for the closed simulation of the dynamic behaviour of AMB supported rotor systems. The modular structure of MLDyn is demonstrated in *Fig. 5*. The interfaces between the modules make it possible to upgrade the simulation tool with additional modules. In that matter, a new module containing the model of the PMB was integrated in MLDyn. The Transformation-module was also upgraded to provide deviations in the level of the PMB. The design of the PMB also influences the model of the rotor dynamics itself. With the rotor part of the PMB, additional masses and a change of the moments of inertia as well as the position of the centre of gravity had to be respected. Those parameters were also considered in the process of modelling the HMBC on the FLP 500 test rig.

Closed Simulation Calculation on the Dynamic Behaviour of the HMBC. The performance of closed dynamic simulations considers the operation conditions of the simulated application. Due to the nonlinearities of AMBs the procedures of start up, normal operation and landing may have different controller parameters. That's why the function of the HMBC has to be approved for at least the following operation conditions:

- start-up and landing operations
- normal operation
- speed levels and unbalances
- axial and radial static loads
- axial and radial dynamic loads

Demonstrating an example of the simulation calculations, the systems response regarding axial rotor position while start-up procedure is plotted in the diagram in *Fig. 6*. The frame conditions of this operation mode were a

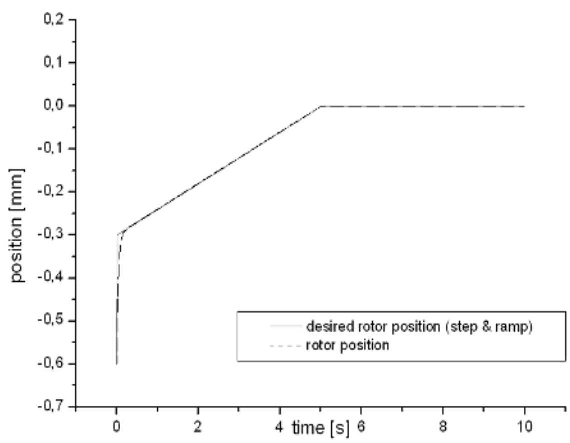

Fig. 6: example for the start-up operation of the FLP 500 test rig

starting position from the Touch Down Bearing using an additional start-up control function that is superimposed on the signal of the set-point-position of the rotor. The smooth behaviour could be reached by use of a fine tuned controller parameter set. These analytical tests were also performed as experimental tests on the FLP 500.

Experimental Tests of the HMBC. The next section of the studies was an experimental part. In the first instance the dynamic behaviour of the Hybrid Bearing System had to be tested. Therefore the test conditions were specified regarding the different operation states, also considered for the simulation. So the scope of the experiments included load tests with static and dynamic loads and operation at different working points. For the purposes of the experiments the test rig was equipped with the PMB on the lower shaft end as can be seen in *Fig. 7*. The results of the experimental tests and particularly the databases from the measurement were used to validate the analytical models of the HMBC. Those validated Models allow the transferability of the determined properties and advantages of the HMBC. That could be done for instance by performance of application specific simulation calculations with MLDyn.

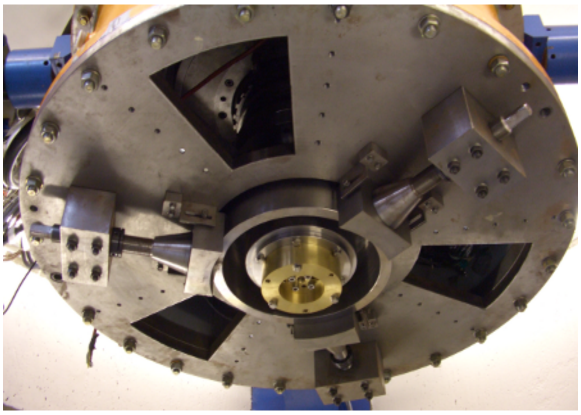

Fig. 7: the PMB assembled on the lower shaft end of the test rig

The second part of the experimental studies was dedicated to the determination of the achievable effects of the HMBC. Therefore the scope of experiments and frame conditions was oriented on specified single tests like varying the axial set-point-position of the rotor or testing the self restoring effects of the PMB. The results of these tests are discussed hereafter.

Selected Results of the Investigations

Indicating the Radial Restoring Effects. For these tests a failure of the lower radial AMB was simulated. Thereby a static radial disturbance was introduced, varying its amplitude and the control system of the lower radial AMB was switched off manually. For the configuration without PMB, the load pulls the shaft into the radial TDB when the radial control system fails (switched off). The same test case, but with the additional PMB is illustrated in *Fig. 8*. In that case the PMB compensates the load of 500 N regarding its radial stiffness and absolute position. Due to the PMBs restoring force the rotor is set to a new stable position. The maximum of controllable static radial loads of the investigated PMB was determined by approximately 700 N where the rotor deviation overruns the allowable limit.

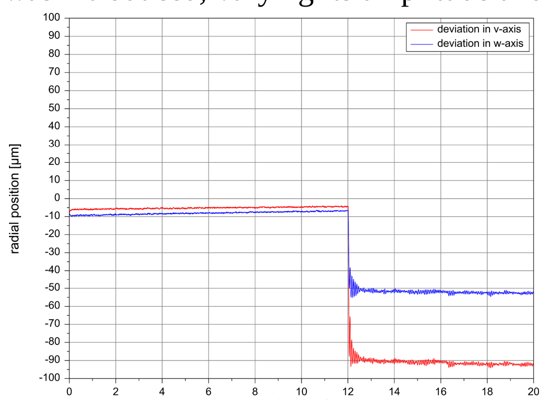

Fig. 8: AMB failure at 500 N radial load, compensated by PMB

Varying the Set-Point-Position. Due to its design, the additional PMB has an axial centre point, where the sum of the axial operating permanent magnetic forces is zero, i.e. where it is stable. It is technically impossible to fix the PMB exactly that position where this centre point is equal to the nominal set-point of the axial AMB. To determine the influence of the set-point deviation from the PMBs centre point, experimental tests were performed without and with the PMB, varying the set-point position z in a range of -200 μm $\leq z_{nominal} \leq$ +200 μm. Thereby the PMBs relative centre point was fixed approximately 175 μm below the nominal set-point. *Table 1* demonstrates exemplarily the comparison of current effort without and with PMB.

Table 1: comparison of current effort for static levitation in the set-point-level

set-point-pos.	*nominal+200 μm*	*nominal*	*nominal -200 μm*
FLP 500 configuration	axial AMB current [A]		
without PMB	19,73	22,35	24,68
with PMB	18,62	21,43	24,29

Table 1 shows for the first two set-point-positions that the current and therefore also the necessary force to carry the dead weight of the shaft are smaller for the case with the additional PMB compared to the other configuration. This verifies the property of the HMBC to provide dead weight compensating forces, when the set-point position is above the critical working point of the PMB.

Conclusions

The magnet arrangement of the used PMB makes a shear force bearing which features radial restoring forces and provides an inherent stable central rotor position. In case of a vertical rotor shaft additional advantage can be taken as well from the negative axial stiffness of this set-up. If the design rotor position for free suspension is adjusted for a smaller gap, i.e. <1mm, between the upper surface of the rotor magnets and the stator magnets than at the lower side, the magnetic attraction will contribute to the rotor levitation.

Summarizing the achieved results it can be outlined that a hybrid magnetic bearing concept is feasible. The control system is able to compensate the instability and missing damping properties that are introduced by the additional PMB. The experimental tests confirm the analytical studies. The magnitude of radial restoring effects can be increased by bigger PMB set-ups. A point to mention is that with the radial PMB additionally to the radial restoring properties also positive effects in axial direction can be achieved.

References

[1] F. Worlitz, T. Rottenbach, et al: Use of magnetic bearings for safety relevant drives, final report, Zittau, Germany, 1997.

[2] M. Gronek, F. Worlitz, et al: A Contribution on the Investigation of the Dynamic Behaviour of Rotating Shafts with a Hybrid Magnetic Bearing Concept (HMBC) for Blower Application, Paper 58045, Proceedings of the 4th International Topical Meeting on High Temperature Reactor Technology, HTR 2008, Washington D.C., USA, 28. Sept. – 1. Oct. 2008.