Safety and Reliability Aspects For Active Magnetic Bearing Applications - A Survey -

Gerhard Schweitzer
Institute of Nuclear and New Energy Technology (INET)
Tsinghua University, Beijing 100084, China
g.schweitzer@ggaweb.ch

Abstract: The application of magnetic bearings for rotating machinery has become state of the art, and spans from research prototypes to industrial series. Users are aware that beyond functionality the aspects of safety and related areas become increasingly important. This survey addresses the issues of safety, dependability, and reliability. It gives a review on existing approaches, and it shows numerous examples of problems and solutions. Review topics are safety-oriented design methods, software tools, redundancy, robust control, and retainer bearings. Finally, the concept of smart machines is introduced to conceive novel ways of further improving safety and dependability of machinery with active magnetic bearings.

Keywords: magnetic bearings, safety, reliability, dependability, smart machines

1 INTRODUCTION

The application of active magnetic bearings (AMB) for rotating machinery has become state of the art, and spans from research prototypes to industrial applications, from small turbo molecular pumps to powerful pipeline compressors in the megawatt range. Users are aware that, beyond function, the aspects of safety and related areas become increasingly important. Safety is more than a mere technical issue. It contains a strong component of psychological interpretation, and expectations as to safety are running very high. Reliability, on the other side, has a definitely technical touch, and it appears to be more amenable to engineering calculations and to economic considerations. Mathematical tools for assessing reliability of classical technical systems, and performance numbers for comparing them, such as mean time between failures, are readily available. The reliability *analysis* of given technical structures and systems, consisting of a more or less large number of classical components, is rather well developed. However, the active magnetic bearing is not a classical technical system. It is a typical mechatronic product, and as such it contains information processing components, software and feedback loops. The reliability analysis of mechatronic system has yet to be developed. In addition, the synthesis approach, addressing the question of how to *design* a safe system, is not structured. There is a good chance, however, to make mechatronic systems, despite their obvious complexity, more reliable than classical ones. It is the potential of internal information processing, somehow resembling the ability of living beings, to use that information to increase the chances of "survival".

The paper will, firstly, address conceptual questions of safety and reliability, in particular, stating that it is theoretically not possible to build a fully safe system. Subsequently it will deal with failure sources in mechatronic systems. With respect to a safe AMB design, it will give a structured survey, with references on details, on how to avoid failures. Eventually, the smart machine technology, with the AMB as a component for the information-processing element within the machine, will be outlined.

2 PSYCHOLOGICAL AND PHILOSOPHICAL BACKGROUND OF SAFETY

Danger has always been an immanent part of human life, and safety, the absence of danger, has been precious. Dangers may come from environmental catastrophes, wild animals, unknown enemies, or unexpected illness. It is a permanent effort of our society to convert danger into risk, to make it calculable and controllable, to tame fate. Dams have been built, to avoid flooding, wild animals have vanished to the zoo, and against illness and death we have at least insurances to mitigate the consequences. Technical means to increase safety in advanced products, nowadays, are mainly based on mechatronic methods. Driving a car has been made safer by mechatronic driver assist systems, which control dangerous situations, such as braking or skidding.

The acceptance level of danger and risk has a strong *psychological background* and varies with emotional attitude, habituation, and individual exposure. Let some examples speak for themselves, without dwelling on arguments or further explanations: car accidents versus train accidents, smoking and drinking habits even against medical advice, danger in hobby sports versus danger in work conditions. In hobby sports, people even enjoy the thrills of risks, be it bungee jumping, or car racing. A nice headline-making example is shown in fig. 1, which could initiate lively discussions on various topics.

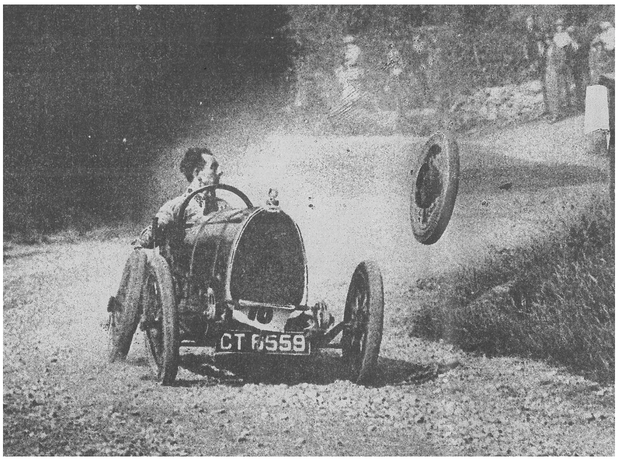

Fig. 1 Car race in Wales, 1924, 90 km/h

On the *philosophical side*, safety might spur some discussion as well. The philosopher Karl Popper [1], in his famous treatise "Logic of Science", 1934, stated, that any progress in science probably is coming from falsifying existing theories and modifying them or stating new ones that correspond better to experience than the previous ones. This means that you cannot prove that a theory is right, you can only try to falsify it or parts of it, and improve the situation. As a consequence, the statement that a system is safe, describes an ideal state that cannot be verified, but only, to some extent, be falsified. It is an uncomfortable insight to many people, that risk is something that, principally, cannot be avoided. However, there are various techniques to reduce risk, in stepwise approaches. These will be discussed in the subsequent chapters.

3 DEFINITIONS AND TECHNICAL ASPECTS OF SAFETY, RELIABILITY AND DEPENDABILITY

Safety is one of the four aspects of *dependability*, a term which has been coined by Laprie (1992) [2]. *Dependability* encompasses *safety, reliability, availability* and *security*. Here, *availability* means the readiness for usage; *security* regulates the access to the system, the authority to operate it, to give commands, and to alter software. In brief, it regulates the communication to the world outside of the technical system under consideration [3].

The areas characterized by the two terms *safety* and *reliability* are somewhat overlapping, as illustrated by fig. 2. Customers, of course, are interested in this overlapping; they want a safe *and* reliable product. The product, the active magnetic bearing system, and its safety aspects will be introduced in the next steps.

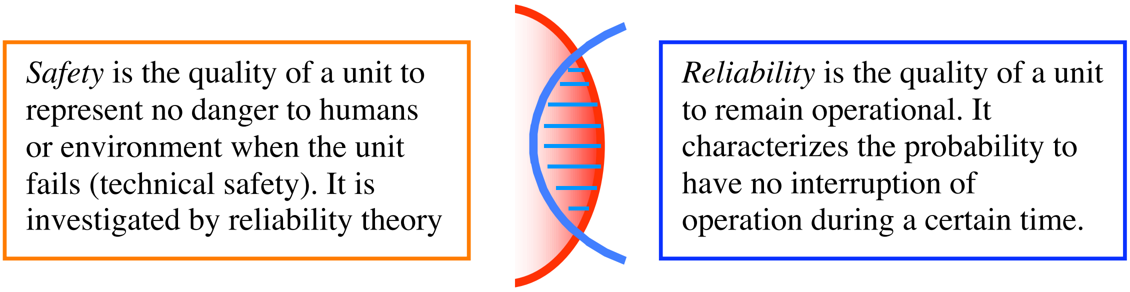

Fig. 2 Definitions of safety and reliability

4 THE AMB AS A MECHATRONIC PRODUCT AND ITS APPLICATION

The active magnetic bearing is a typical mechatronic device, consisting of mechanical, electrical and information processing elements. Its function principle, as shown in fig. 3, is rather simple. Its main characteristic is the control loop to generate electromagnetic forces, which keep the rotor, with no contact, in a stable hovering position. The properties of this dynamic process are determined by the internal information processing of the microprocessor, i.e. by appropriate control software [4].

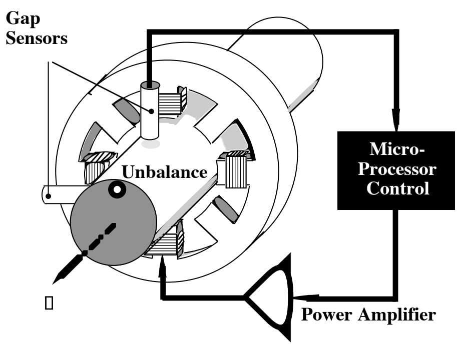

Fig. 3 Principle of Active Magnetic Bearing (AMB)

An application area actually already well established and developing rapidly further are turbo machinery. Products range from small turbo molecular pumps to large compressors for pipeline gas, and to turbo generators for power plants. A recent research project of international interest is the turbo generator in AMB for the High Temperature Helium Reactor technology. Even though the underlying nuclear technology is inherently fail/safe, safety requirements are obvious.

5 FAILURE EXAMPLES IN MECHATRONIC SYSTEMS AND AMB

Due to the specific structure of mechatronic systems we may have failures in the mechanical elements, the electronics, or in the software. A few examples from the AMB experience will be given to illustrate the scope of potential failures.

Examples for *software failures* are a system breakdown, run-time exceptions, i.e. address errors and bus time-out, or incompatible program versions. The software area is least covered by systematic approaches to improve its reliability. Concepts will be discussed later.

The *electronics* may fail or the signals may be disturbed, most often by excessive noise from electromagnetic sources, which are mistaken as sensor signals. The area of EMC (electro magnetic compatibility) is to be taken most seriously, considering the high-powered switched amplifiers in the AMB loop, but the means for dealing with these problems are more or less standard and will not be addressed further. Defects in the microprocessor hardware, or disturbances in the power supply are to be taken into account (see chapter 6.4 – 6.7).

For *mechanical failures*, there is a wealth of experience and established procedures to avoid them. The break down of mechanical parts, i.e. a blade loss or a rotor crack, or a leakage in a cooling system are failure modes well known from classical rotor design and can be dealt with in conventional ways. Two major sources of excessive mechanical loads, however, shall be mentioned in particular. Centrifugal forces at *high rotor speeds* will lead to limitations, as characterized in fig. 4. Higher circumferential rotor speeds – a recent example are 380 m/s for the motor drive – require special design efforts such as carbon fibre bandages around the rotor.

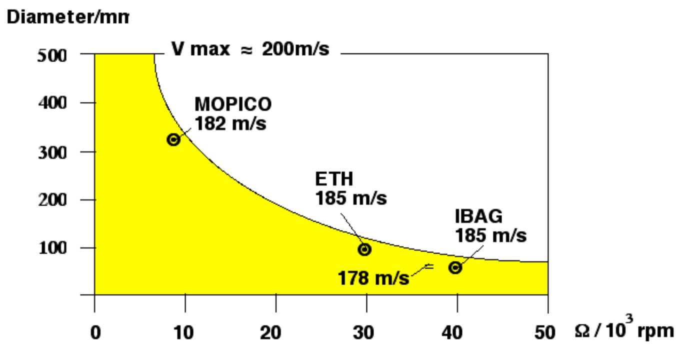

Fig. 4 Example for the limitations of high-speed rotors, in rotor diameter and rotation speed □, as caused by the strength limit of the material. Examples indicate various applications [5]. The one rotor at a circumferential speed vmax = 178 m/s failed due to a poor design of the motor drive.

The other excessive load can be caused by contacts of the high-speed rotor with its *retainer bearings*. Some remarks on retainer bearings will be made in chapter 6.7. Subsequently, methods and means for reducing the risk of failures will be summarized.

6 MEASURES FOR REDUCING RISKS OF FAILURE

The different measures range from systematic design procedures, software development tools, redundancies, individual measures, and quality control to the smart machine concept, which includes various control strategies, active fault diagnostics and corrections. These measures will be described briefly in this and the next chapter. More details on the classical approaches are given in [6].

6.1 Quality control, standards

An overall approach for systematically introducing quality aspects into the design, production and operation of products and systems, are standardized procedures as described in the ISO 9000 series [7]. A company or an establishment following the procedures of ISO 9000 can be recognized as a certified institution with a defined quality level.

In addition, there is the ISO 14839 on AMB (Mechanical vibration -- Vibration of rotating machinery equipped with active magnetic bearings [8]). Part 1, on the vocabulary, has been published; further editions are under development by the ISO Technical Committee 108, Working Group 7, under the direction of O. Matsushita. Standards help to avoid misunderstandings and contribute to quality management.

The field of AMB is still very young, and therefore company specific guidelines are important elements of quality control. For specific applications, drop tests into retainer bearings, temperature and vacuum tests are being performed.

6.2 Systematic check of the design

A classical method to ensure best practice of the state of the art is to use the FMECA approach for checking the design, i.e., to do a Failure Modes, Effects, and Criticality Analysis. In this approach a group of experts with different background, from design, production, test, repair, and potential users, are evaluating the design or the product. They have to point to potential failure modes, determine the effects and consequences of such failures and their criticality, and suggest modifications of the design to improve it. There are various standards and specifications on how to proceed in detail, depending on application areas (see for example the military standard procedures MIL-STD-1629A). FMECA is an integral part of any QS 9000 compliant quality system.

6.3 Software development system

In a mechatronic product software is an integral part of the product, it is a component of the machine. It has to be developed and implemented. Of course, the software has to be logically correct, and the operating system should take care of the syntax. But in addition to that, the correct time sequence of the computational tasks is most essential in real time applications.

For *industrial AMB applications* most often proprietary software is running on single chip Digital Signal Processors (DSP) giving an efficient and economic solution. The software is streamlined and dedicated to specific tasks with well-defined constraints.

For *experimental set-up* the tasks usually are much more diverse and sometimes complex, and ask for a versatile solution. For complex tasks it may not be sufficient to just use a high-speed computer with high sampling frequency and to hope that this is adequate for real time operation. It might be better to use a Real Time Operating System (RTOS) from the onset in order to develop and finally operate the software. Such RTOS are available in various versions, such as RT Linux, XO/2, dSPACE, and VxWorks, differing in complexity, overhead size, speed, price, and availability.

The *design of software* is still an "art", like any design process. Nevertheless, there are a number of accepted ways for designing complex software professionally, and even for validating it. One way of reducing the probability of errors in the software design is a development system as shown in fig. 5 [9]. The designer preferably makes use of software packages from his libraries, configuring them interactively with graphical tools. The RTOS being used is the same for the design and the later process application, allowing for meaningful simulations and emulations, fast modifications and realistic tests. Such a software package for rapid control prototyping, very versatile and useful for the design of embedded systems, which includes signal processing tools and actuator drivers, as well, and allows hardware in the loop tests, is described in [10].

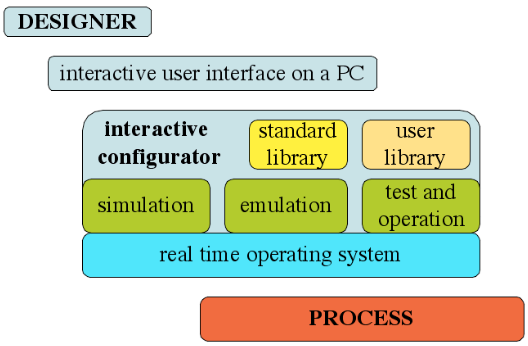

Fig. 5 Concept for a software development system for embedded microprocessor

In addition, the development system with its extensive modelling of the rotor in active magnetic bearings facilitates the *simulation of design variations*, aiming at an optimization of safety features. As there are may ideas and suggestions on how to avoid or monitor faults and improve safety, these means, before implementing them in hardware, should be investigated for their usefulness. This includes control variations to accommodate disturbances and faults, exception monitoring and handling devices such as watchdogs, the optimizing of sensor and actuator locations, or the arrangement of redundant components.

6.4 Redundancy

One way of improving reliability is to use *redundant components* and *redundant information*. There are two different kinds of redundancies. If the failure of a single component cannot be corrected and is critical for the system's safety, the function of this component should be guaranteed by redundant hardware. Two or more of these same components have to be arranged in parallel, in order to replace any failed component (fig. 6, left). Appropriate failure detection and switchover schemes are crucial, and the increase in the number of components actually counteracts the overall reliability to some extent. If the function of a component is at least partially performed by another component as well, then the functional relation between these components can be used as an analytical redundancy to replace the failed component partially, or to reduce the extent and cost of a hardware redundancy (fig. 6, right)

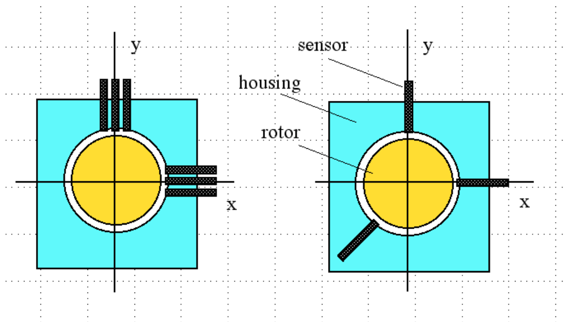

Fig. 6 Cross-section of the rotor/bearing with redundant sensors [9]
Left: hardware redundancy with triplex sensor configuration.
Right: analytical redundancy, simplex sensor configuration with one redundant sensor

In magnetic bearing technology both redundancy schemes have been investigated, and some examples will be cited subsequently. For future *aircraft engine applications* a redundant magnetic bearing structure has been suggested [11]: Each radial bearing has three independently controlled axes. The controller consists of two hierarchical levels, a supervisory level and an actuation level. The supervisor controllers are configured in a duplex fault tolerant configuration, one controller is active, the other in standby mode. For *industrial applications*, an AMB supplier offers duplex hardware redundancy for the central controller. The switchover time between the active and the standby controller is about 500 ms, considered to be short enough to avoid overheating of the retainer bearings during a possible, brief touch down. The second controller is supposed to recover the rotor and bring it back to normal operation. *Further investigations* deal with multiple sensors, with redundant flux paths in the case where an electromagnetic coil fails [12-15]. In [16] controller fault tolerance is achieved through a very high speed voting mechanism which implements triple modular redundancy with a powered spare CPU, thereby permitting failure of up to three CPU modules without system failure. Using a separate power amplifier for each bearing coil and permitting amplifier reconfiguration by the controller upon detection of faults achieve amplifier/cabling/coil fault tolerance. This allows hot replacement of failed amplifiers without any system degradation.

With the growing experience in AMB technology and the advances in control techniques the emphasis of reliability design has been shifting from hardware redundancy design to software based robust and fault tolerant systems, making the AMB a key component in smart rotating machinery (chapter 6.6 and 7).

6.5 Exception handling, watchdog

The occurrence of singular, exceptional events and failures of safety-critical components has to be detected in order to introduce countermeasures. In a classical approach, a “watchdog” is monitoring the actual behaviour and comparing it to the expected normal operation, giving alarm when deviations occur and initiating a switch-over to a safe operating mode. As an example, a *failure of the power supply* has to be considered as a serious exceptional event, and it can be compensated for by various means. One way is the switchover to a second power supply such as a set of batteries or condensers, being part of a classical UPS (Uninterruptible Power Supply). Another way is to make use of the rotational energy stored in the rotating rotor. If the rotor is driven by a motor drive, switching the motor from its drive mode to generator mode can supply sufficient electrical power to the system again, until the rotor can coast down safely in its retainer bearings [17]. There may be other special subsystems in an AMB/rotor system for exception handling, deserving a separate investigation, but in general these tasks will be integrated into a smart system concept.

6.6 Robust control

The design for robust control of the AMB should allow for *uncertainties* in the system parameters and for a variety of *disturbances* acting as additional inputs to the sensors that classical control cannot handle any more. The uncertainties may arise in the bearing characteristics changing with temperature, the rotor mass being modified by the inertia of gas being transported in a turbo-machine, or the damping characteristics of a flexible rotor. The disturbances acting as strong additional inputs are most often from external sources. They may arise from motions of the machine base caused by earthquake or from using an AMB/rotor system in a moving vehicle, or from tool-generated forces in a milling process. Robust control most often requires a high order controller; methods for the design of robust H_∞ control are given for example in [18], a robust μ-synthesis AMB application is detailed in [40]. Further examples are cited in chapter 7.

6.7 Fail-safe system, retainer bearings

The best way to build a safe system is to make it fail/safe. This means, that if anything goes wrong, eventually and as a last resort, the system will degenerate to a safe system, it will be naturally safe. An airplane, for example, is not a fail/safe system. This is the main reason why AMB systems are equipped with retainer bearings. Retainer bearings are an additional set of conventional bearings, and the rotor will only come into touch with them when the contact-free suspension in AMB is not working, or fails, or under heavy overload. The dynamics of a high-speed rotor dropping into the retainer bearings is strongly nonlinear. The contact forces can become quite high, and if the friction between the spinning rotor and the retainer bearing is too high a violent and destructive backward whirl can develop. Heavy overload can even occur as part of the “regular” operation in so-called “load sharing bearings”. In such AMBs for future aero-engines heavy loads are expected during high acceleration flight manoeuvres, and during landing shocks. Control for the AMB has to be switched from no contact mode to contact mode, not to recover the rotor but to share the load with the retainer bearing in a stable and efficient way [19].

There is much literature on retainer bearings and the associated rotor dynamics, and only part of it will be cited here. The friction induced rotor backward whirl was described by J.P. den Hartog in his book on “Mechanical Vibrations” in the 1920th already. Another milestone was the work of Black [20], and up to now there are many results on modelling the rotor dynamics caused by the contact with the retainer bearings or the housing [21-26]. Testing such retainer bearings has been described in [27-30], and suggestions for the retainer bearing design for various applications are given in [31-34]. For standard applications quite satisfying results have been obtained, and retainer bearings are being industrially implemented.

Some *guidelines for the design* of retainer bearings will be summarized: Low friction is essential. Good results have been obtained with ball bearings with coated balls or made of ceramics, no caging of the balls to reduce the inertia when the bearing elements have to be accelerated toward the touch down rotor speed, and higher internal clearance to allow for thermal expansion. The landing sleeve should be made of high strength material and have a surface with low friction and great hardness, the support-structure should be rigid to maintain alignment, and the retainer bearing should be kept clean from contamination. For damping the impacts special components have been designed. Contact time has to be kept short to avoid overheating of the retainer bearings, and therefore the rotor should be actively slowed down or recovered by control actions. However, the optimal design of retainer bearings still relies mostly on experience, and a systematic, generally accepted design procedure has yet to be developed.

A question closely related to the design of retainer bearings and to the touch down behaviour of the rotor is the associated *control of the rotor dynamics*. It is of interest to recognize the impending of a contact and, if possible, to modify the control in order to avoid the contact, or after a contact has occurred to recover the rotor or to enable a stable load sharing by suitable control actions. Results have been obtained and will be discussed in the next section.

7 SMART MACHINE TECHNOLOGIES

The basic idea of mechatronics, of combining mechanics, electronics and information processing within a product in a synergetic way, has led to the concept of smart machines, where the capability of internal information processing is used in an extensive way. The use of this concept in AMB applications has been shown in [35], and a definition might run as

> Smart machines know their internal state and optimize it by internal information processing. This leads to better functionality with features such as self-calibration, self-diagnostics, self-tuning, self-corrections, and associated with it to less maintenance and higher safety.

A block diagram illustrating the structure of such a machine is shown in fig. 7. The diagram has been developed by R. Nordmann for a European Research Project [36].

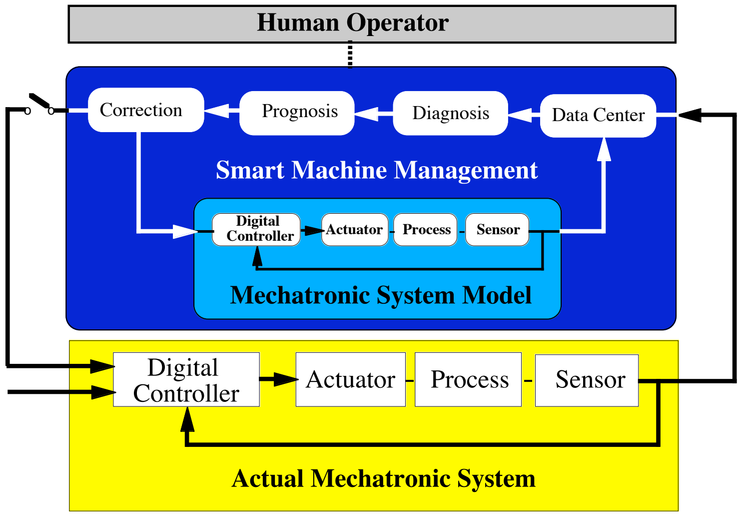

Fig. 7 Block diagram of a smart machine

The smart machine in fig. 7 consists of three main parts. One is the "Actual Mechatronic System", the real machine with its process, sensors, actuators and the controller. In our case this would be the rotor of a machine tool or a turbo-rotor in magnetic bearings.

The second part is the "Mechatronic System Model", a software representation of the real machine. Of course, setting up such a model may not be simple, and that is why identification techniques are an important tool in this technology. The model, or a part of it, will be used for designing, modifying or reconfiguring the control of the real machine.

The third part describes the "Smart Machine Management". It indicates the additional functions that can be conceived by making "smart" use of the available information. At first, data have to be collected from the real machine and its sensors and from the model as well which runs in parallel to the real machine. Based on this information a diagnosis of the present state will be possible. It can be a model-based diagnosis, a method that has been investigated for rotating machinery in a BRITE/EURAM project [37]. Furthermore, due to the built-in control loop, self-diagnosis or active diagnosis will be possible, i.e., it will be possible to check hypotheses about parameters or faults by creating suitable test signals for the model and for the real system. This approach could further improve identification procedures, and it will be of interest for reliability management, for finding out about failures in mechanical components such as cracks in the rotor, or about failures in electrical components, for example in sensors, or about other exceptional situations. Based on the results of diagnosis, a prognosis about the future behaviour of the machine or about the need for and the consequences of corrective measures can be derived. Such corrections, for example, could be the compensation of an unbalance, special procedures for passing critical speeds, changing the feed of a machine tool during the manufacturing of delicate parts by taking into account the cutting forces or tool wear, or it may even lead to a self-tuning of the parameters of the actual control loop. Some examples will demonstrate the state of the art and actual research topics.

Identification procedures have been developed for multivariable AMB systems [38], at first, to identify the structure of the unstable open loop system during closed loop operation. The results have been extended and used to derive in an automated, iterative way a robust controller for a flexible rotor [39]. The experimental set-up being used is shown in figs. 8 and 9. The set-up represents a realization of the structural block diagram of fig. 7. In addition to the control loop for supporting the rotor, a diagnosis and a correction module have been implemented.

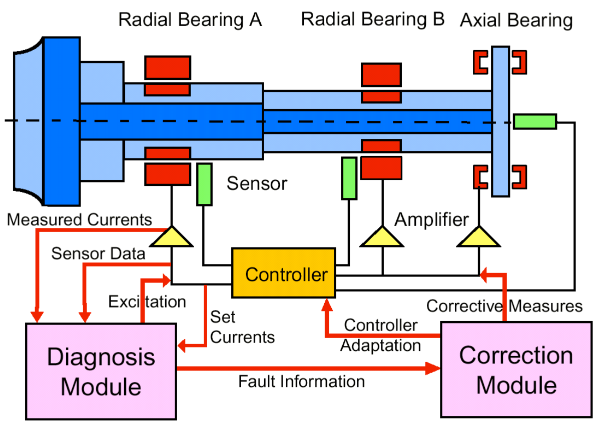

Fig. 8 Rotor in AMB with additional smart machine modules for diagnosis and correction

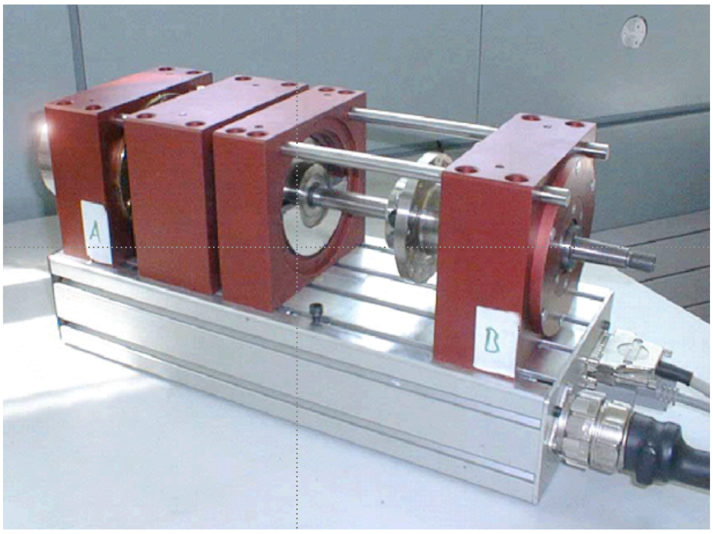

Fig. 9 Test rig for smart machine technology [39, 43]

Diagnostics and identification tools are being used as well for fault detection of various kinds and for the development of fault-tolerant control. A general introduction is given in [41, 42]. Examples with respect to AMB cover already a wide range and are cited below:

An already nearly classical issue is the unbalance compensation. It uses learning procedures and estimation techniques as diagnostics tools. For the correction, or rather compensation of the unbalance signal in the sensors, a feed forward control signal is generated. The compensation technique has already reached a high performance level, is industrially available and will not be detailed here.

In magnetic bearings, faults in sensors and actuators and other machine components have been detected and corrected [43-47].

The malfunction and the wear of tools in a milling process have been diagnosed from sensor signals of the AMB-supported milling spindle [45]. Thus, the AMB can be used to detect even faulty process parameters, which are not directly related to the functioning of the AMB itself, and the AMB can contribute to the reliability of the whole machine and its working process.

The dynamics of a rotor touching upon a retainer bearing has been described in [25], and based upon this model, as a correction measure, the control is reconfigured in order to recover the rotor [46]. A different correction procedure would be to avoid the potentially critical touch down, i.e., to detect the impending contact and to reconfigure the control suitably on time to keep the rotor out of touch [47]. It can be expected that these approaches will be extended in theory and application and will strongly contribute to the overall safety performance of the AMB technology.

8 CONCLUSIONS

Safety of a product is an ambiguous term that requires considerations from a user's point of view. Some of these aspects have been addressed. Philosophical reasoning on the logic of science shows that safety can only be improved, step after step; it cannot be guaranteed.

Then, main emphasis is put on the technical side of safety and reliability for AMB/rotor systems. A survey is given on potential risks and error sources. Means for reducing the risks of failure are discussed. First, safety and reliability are put into the framework of quality management and design, and then more specific ways of dealing with AMB are considered. Redundancy schemes, exception handling and robust control are proven tools, and examples are given. The fail/safe operation of an AMB requires additional retainer bearings. The state of the art in modelling the nonlinear rotor dynamics in contacting the retainer bearings, drop tests, and design for specific applications are referenced. Guidelines for the design of retainer bearings are summarized. The area still needs further research.

The potential of AMB/rotor systems to become fault-tolerant is seen as a general feature of smart machinery. Smart means, that such a machine knows its state – as it already has sensors and internal control loops for its functionality - and makes best use of the internal information processing capabilities within the machine to optimize its state. Examples on the design of fault-tolerant AMB, using diagnostics, identification methods and reconfigurable control are discussed and referenced. It is expected that future research will support these trends and make them available for further applications, contributing to the already very impressive, but still growing, safety and reliability features of AMB.

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Corresponding address:

Prof. Gerhard Schweitzer
Lindenbergstr. 18a
8700 Kuesnacht
Switzerland
email g.schweitzer@ggaweb.ch
Tel./Fax ++41-43-266 94 83
http://www.mcgs.ch