Activities of ISO/TC 108/SC 2/WG 7 in the Development of Standards for AMB Systems

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Abstract— **ISO/TC 108/SC 2/WG 7 is the official working group of the International Organization for Standardization (ISO) that deals with the setting of standards for Active Magnetic Bearing (AMB) equipped rotating machinery. Since 2002, four parts have been developed for ISO 14839 covering Vocabulary (Part 1), Evaluation of Vibration (Part 2), Evaluation of Stability Margin (Part 3), and Technical Guidelines (Part 4). This paper will provide an update on progress for Touchdown Bearings for Rotating Machinery Equipped with Active Magnetic Bearings (Part 5). The paper will also provide an overview of the expected future development of the standard, including the important issues that need to be addressed in the design process.**

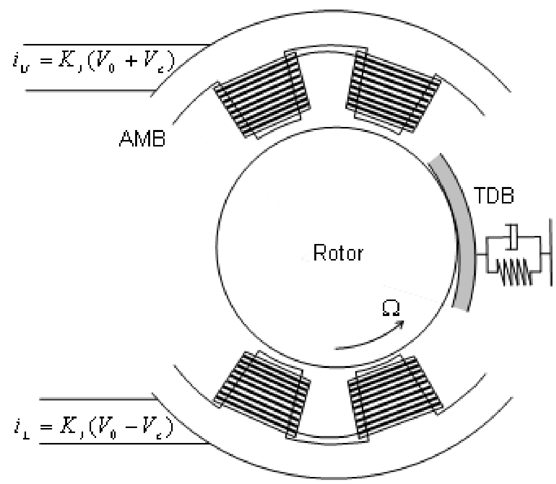

Figure 1. Cross-section schematic showing an AMB levitated rotor making contact with a Touchdown Bearing (TDB).

A. Introduction

There is an increasing number of applications for AMB equipped rotating machines, including compressors, steam turbines, turbomolecular pumps, motors, generators, flywheels etc. In principle, with appropriate system design and correct measurement of rotor displacements for feedback through a robust controller, the rotor will levitate and the machine will operate without loss of functionality [1-4]. However, fault conditions, overload conditions, and other abnormal influences may cause the rotor to make contact with touchdown bearings (TDBs). These are typically incorporated adjacent to AMBs and have radial clearances that are less than the AMB magnetic gaps. Figure 1 shows a schematic of this scenario. The rotor has made contact with a TDB, which may be resiliently mounted. The TDB may therefore deflect and its role is to prevent contact with the AMB stator poles and other close clearances within the machine during intermittent contacts and during full run-downs. The rotor dynamics during contact may be severe, both in terms of mechanical and thermal stressing. These are limiting factors for TDB durability and residual life. The TDB is therefore a sacrificial component that may be replaced after a specified number of touchdown events. However, outage periods may be costly in terms of missed productivity. As a result, TDB design is a special consideration for AMB applications.

B. Background Literature

AMB systems embed mechatronic principles to achieve contact-free levitation of rotors [5], in principle, without wear. This functionality enables a number of high speed applications without the need for any lubricant, for example, in turbomachinery, compressors, motors, flywheels and vacuum pumps. Given the developments in the field, international standards are now available to specify system design, performance and stability of operation [1-4].

It is clear that if an AMB ceases to function, intentionally or unintentionally, a rotor drop onto a TDB will occur. A number of important studies, including tests on an industrial scale, have been undertaken to investigate this condition [6-13]. Simulation models of the rotor/TDB contact under rotor drop have also been developed [14-23] and these are able to yield detailed predictions, particularly for rolling element TDBs. Other types of TDBs are commonly employed, including bushing designs. Under the conditions of rotor drop,

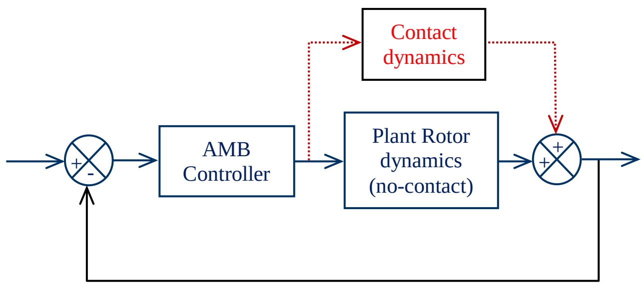

Figure 2. The AMB controller shown could be designed for a no-contact plant. However, disturbances induced by rotor/TDB contact dynamics may propagate by feedback to cause closed loop instability.

the rotor landing sleeve and TDB surfaces may experience high mechanical and thermal stresses during the rotor run-down period, which require special materials to be used in the TDB construction. The accumulated damage to a TDB may be significant such that operational life is commonly specified in terms of a maximum number of rotor drop events.

Other touchdown events may be less severe, and they may arise while the AMB system is fully functional. These include intermittent faults associated with feedback signals, shock events, or overload conditions. For example, base excitation predictions and tests are reported in [23]. However, it should be realized that the rotor dynamic plant will be different compared with the contact-free levitated case, hence the AMB control may not be appropriate to deal with such a case. Figure 2 provides an indication of the control problem. The rotor dynamic conditions may develop to the point where initial rotor bouncing continues or changes to low frequency rocking, forward whirl, backward whirl, or a combination of these with bouncing. In the forward whirl case, contact forces may become large if the frequency is high, hence TDB damage will be accumulated. The case of backward whirl usually involves high frequency content and the contact forces may be extremely high. Given that the AMB system remains functional, it is appropriate to consider control options that are available in order to prevent persistent rotor contact dynamics.

Other academic research has been undertaken with active TDBs [24, 25], which have been shown to be capable of alleviating contact forces. However, these have yet to be adopted for industrial applications, the current state-of-the-art being restricted to TDB passive mounting design. The passive characteristics may be used to influence the rotor dynamic response during touchdown, however, this will be limiting in terms of what can be achieved.

In this paper we discuss the international standard ISO 14839-5 currently under development. It has a special focus on the complex issues associated with TDB integration into AMB equipped rotating machines. It provides an update on the current thinking and anticipated areas for attention.

C. Scope of ISO 14839-5

The scope of Part 5 of the standard includes:

a) the typical architectures of TDB systems to show which components are likely to comprise such systems and which functions these components provide;
b) the functional targets required of TDB systems so that clear performance targets may be formed for TDB systems with an unambiguous terminology for such performance targets;
c) elements to be considered in the design of the dynamic system such that rotor dynamic performance can be optimized, both on TDBs and on AMBs;
d) the environmental factors that have significant impact on TDB system performance allowing optimization of overall machine design;
e) the AMB operational conditions that may give rise to contact within the TDB system so that such events can be considered as part of an overall machine design. It also considers failure modes within the AMB system that may give rise to a contact event. This ensures the specification of the TDBs covers all operational requirements;
f) the most commonly encountered failure modes within the TDBs and typical mechanisms for managing these limitations;
g) typical elements of a design process for TDB systems including the specification of load requirements, the sizing process, the analytical and simulation methods employed for design validation;
h) the parameters associated with acceptance testing of TDB systems which should be considered during the design of such tests. This includes the test conditions and associated instrumentation to ensure successful execution of such testing;
i) the condition monitoring and inspection methods that will allow the status of in-service TDBs to be evaluated and corrective actions to be taken when necessary;
j) the factors to be considered when designing the maintenance regime for a TDB system. This includes actions to be undertaken following specified events together with any actions to be performed on a regular basis.

D. General Structure and Components

Rotating machinery equipped with AMBs is typically also equipped with TDBs. The TDBs are intended to support the rotor when the AMB system is not activated or during a failure or overload of the AMB system. In these instances the TDBs are required to support the rotor until either levitation is recovered or the rotor is brought to zero rotational speed without damage to other parts of the machine. In some instances a prolonged reduced speed capability is required.

During normal operation of the machinery the TDBs will have a clearance to the rotor and will consequently not apply force to the rotor. The clearance at the TDBs is typically the closest clearance within the rotating machine. This ensures in the event of a problem with the AMB, when the rotor moves away from its normal “centred” operating position, the first item to make contact between the rotor and stator is the TDB. Such an event occurring during rotation is referred to as a “touchdown event”, “landing event”, “contact event” or “drop event”.

TDBs have been based on a range of technologies, such as:

- Stator mounted rolling element bearings
- Rotor mounted rolling element bearings
- Dry lubricated plain bushings
- Dry lubricated pad constructions
- Foil bearings
- Aero-static bearings

- Fluid film bearings
- Hybrids of the above technologies

In most instances on large machines the TDB will comprise a rotor part (commonly referred to as a landing sleeve) together with a stator part. The landing sleeve is intended to ensure that no damage to the core shaft occurs and will typically be a replaceable item. An alternative to the landing sleeve is to land directly on the shaft surface, which has a wear resistant coating or treatment.

The stator part will typically comprise a low friction element, which contacts the landing surface and is supported by a compliant element. The compliant element has an associated stiffness and damping which is intended to improve vibration response during a touchdown event.

The compliant element may have the following characteristics associated with it:

1. Pre-load
2. Stiffness
3. Damping
4. TDB hard-stop clearance

When considering the minimum design clearance at any axial location, the total rotor motion at the TDBs, which includes the clearance and the TDB hard-stop clearance, should be considered together with other system stiffnesses and tolerances/concentricities.

The condition of the TDBs can be of utmost importance in case of an AMB failure. They must be able to safely bear the rotor during an event such as momentary contact or a full coast down to standstill. The stringent operational demands such as high acceleration rates and high forces lead to a very limited allowed number of such events and thus the TDBs are considered consumable parts. However, replacing TDBs which have not yet reached the end of their lifetime should be avoided. Therefore condition monitoring of TDBs is essential.

E. *Functional Targets*

The setting of the standard requires that tangible functional targets must be set for users to be able to verify for their AMB systems. These will be covered under the following sections.

(a) Design life

This section will address the definitions for the number and severity of touchdown events that a TDB must sustain without replacement in a given application. This will include consideration of the duration of contact ("hard landings" and "soft landings"), and how data are blended together to characterize cumulative damage. This section will also address TDB life in standby (no contact) condition.

(b) Clearance control

This section will address the requirements for minimum and maximum clearances at the TDBs, including mounting compliance. Equivalently, these are the maximum excursion of a rotor without contact with TDBs and maximum excursion including contact. Here, excursion refers to relative rotor-stator motion at the TDB location. These limits should be designed to ensure that no unintended contacts occur between the rotating and non-rotating elements at other locations. Large radial excursions at axial locations other than the TDBs even without contact may, in some machines, need to be prevented by the TDBs. Misalignment tolerances between TDBs and other critical clearances must be defined.

(c) Life-cycle requirements

This section will address the definition of requirements for inspection, maintenance, spare parts and replacement.

F. *Design Considerations*

The design of a TDB system that is to be integrated into an AMB levitated machine will depend on the machine application, its operational requirements and capability to withstand expected abnormal disturbances.

1) Trigger events

TDBs are included with AMB systems to provide backup or auxiliary rotor support in the rare situations where the AMBs cannot completely control the rotor. These situations where the TDBs must provide support for the rotor are driven by a number of abnormal conditions. These conditions, referred to as trigger events, are defined as follows.

(a) Overload due to an abnormal process condition

AMBs have a limited peak load capability characterized by saturation in their ferromagnetic pole pieces. When loaded beyond saturation, the rotor falls out of support and must be retained by the TDBs to prevent damage to the machine. Overload may be due to an abnormal process condition or unexpected external loading source. In many cases, design margins can be included in the AMB sizing to provide extra capacity for such events; however, it is important to avoid providing substantial unneeded capacity in an AMB system. Oversized AMBs may lead to poor actuator bandwidth, undesirable rotor dynamic characteristics, and less robust control. Some common sources of overloading force are mentioned below.

(i) Surge in a compressor

Although surge in compressors is reasonably well understood, when it occurs the imposed load and frequency of thrust imposed is difficult to predict and depends on factors that may not always be in the machine designer's control. To account for surge in design, some estimate has to be made for amplitude, excitation frequency and occurrence frequency of surge events. In some cases, surge will result in short term or intermittent contact with the TDBs (also called touch-and-go) followed by recovery to continuous operation on the AMBs.

(ii) Shock from seismic events, explosions, or impact from mobile equipment (forklift, etc.)

These events are difficult to predict and may vary widely in magnitude and bandwidth. An AMB system can be designed for specific seismic requirements, but seismic events beyond the design requirements will result in TDB impacts. Occasional large shocks in systems subject to explosions or external impacts are generally expected to be absorbed by the TDBs.

(iii) If shock overload is expected, a design amplitude and duration should be defined for analysis

This design case should be a bounding envelope for all expected shock spectra. Thus a system designed to cope with this bounding case should be able to withstand all expected shock inputs.

(iv) Sudden imbalance from benign partial loss of built up of solids from process flows

Some turbomachinery processes result in solids build-up on rotor surfaces. Portions of this build up can flake off during operation resulting in a sudden unbalance. Often the resulting imbalance will be small enough to be acceptable for steady state operation on the magnetic bearings, but the impulse created may produce a short term or intermittent contact on the TDBs.

(v) Sudden imbalance from loss of a turbine blade or other partial failure

A failure of this type will usually result in an unbalance load that is well beyond the capability of the magnetic bearing system and will result in a substantial initial impact load on the TDBs, followed by a full speed spin down on the TDBs. For some types of machines a blade out failure may be a design load requirement for the TDBs.

(vi) Abnormal motor loads – phase imbalance

For machines driven by electric motors, a phase imbalance can result in a radial load on the rotor that doesn't exist in normal operation. Loss of a phase during operation can result in an impulse load that overloads the AMBs, resulting in TDB contact.

(vii) Rub at machine close clearance

In an AMB machine, the TDB clearance should be set such that any excursion of the rotor from center result in TDB contact before any other stator element. Efficiency requirements in turbomachinery encourage seal clearances to be minimized such that the next closest clearance in many machine designs. Rubbing contact with a seal can occur when the design hasn't allowed for adequate clearance margin or seal concentricity relative to the TDB.

(viii) Liquid slugging

In some processes, a slug of liquid may be introduced in the machine causing a shock or impulse load that causes TDB contact.

(b) Instability of AMB control

The nature of AMB compensator design is such that there will often be frequency bands or operating scenarios where the AMB forces will produce negative damping for one or more natural modes of the rotor/AMB/housing system.

(i) Inadequate control robustness to cover process variations

The process variations that are considered to be typical include:

- Aerodynamic forces in compressor, turbines and labyrinth seals can be de-stabilizing under certain conditions (often characterized by cross-coupled stiffness)
- Process fluid density much higher than predicted resulting in higher destabilizing forces
- Variation in suction pressure results in higher destabilizing forces

(ii) Lack of slew rate margin to cover required loads

To respond to dynamic loads an AMB has to produce a certain control current at a required frequency. As the frequency increases the required voltage to push the required current through the control increases. Since power amplifiers are sized with some specific overhead (or bus) voltage, the voltage demand of a particular load may exceed the available overhead. In this case the current is limited by the maximum dI/dt or current slew rate. This situation almost always leads to TDB contact.

(iii) Lack of power supply capacity to cover axial dynamic loads

AMBs generally impose very low real power requirements compared to other types of bearings. Additionally, in most cases it is straightforward to provide an adequately sized power supply with margin to cover unexpected loads. However, if process conditions impose significant and unexpected axial dynamic loads, the power requirements may exceed standard margins due to eddy current losses (which use real power) in the thrust bearing.

(iv) Operation of a machine outside of defined speed range

In highly gyroscopic machines, such as those with single overhung impellers, the AMB control may be gain scheduled. In this case the control is adjusted based on spin speed. If the machine is operated above the expected speed one or more rotor vibration modes may become unstable, resulting in TDB contact.

(v) Unexpected machine acceleration/deceleration profile

During excess acceleration/deceleration aerodynamic forces may be much larger than designed for.

(c) Loss of power

AMB systems require a power source to operate. Loss of power will result in deactivation of the amplifiers and shutdown of the control system. If this happens, the rotor will drop to the TDBs. Generally, some type of backup power is part of the system design, so that the AMBs will operate to allow spin down when external power is lost.

(i) Systems with no backup power source

If no backup power source is provided, a loss of power will result in a rotor drop onto the TDBs at speed.

(ii) System with an uninterruptable power supply (UPS)

Many systems have a UPS sized to allow spin down on the AMBs in the event of power loss. In these systems, power loss should not be an issue unless there is a defect or failure of the UPS.

(iii) Systems that incorporate a motor/generator often have a regenerative backup system

Such a system can generate enough power to supply the AMB in the event of power loss; however, these typically drop out below a certain speed, often 20-25% of maximum speed. Such systems will generally have a relatively benign low speed drop as part of a system power loss event.

(d) Failure in AMB system

Failure in some part of the AMB system will generally result in a drop and spin down on the TDBs. Depending on the action taken by the controller, this may be either a full five-axis drop or a drop of one or more axes followed by a spin down request from the AMB controller.

(i) AMB controller component

Failure of the power supply or a failure that stops the control program will always result in a five-axis drop. Other component failures will generally result in loss of control on one or more axes, followed by either a full or partial drop – depending on the control action taken.

(ii) Actuator or actuator cable failure

An actuator short or open circuit will result in the inability to apply a reaction force to the rotor. This will result in a loss of control and be detected as an excess displacement, excess control current, or low power supply voltage and result in a drop.

(iii) Sensor or sensor cable failure

A sensor/transducer failure may result in an undesirable control action that applies the full force of the AMB to push the rotor into the TDBs, adding an additional impact and static load to the TDB loading.

(e) Mis-operation

Since it may not be possible to ensure that normal operation can be guaranteed, the mitigation of the following issues should lead to more robust systems.

(i) Process flow spins rotor while AMB is disabled

In this case, the rotor spins on TDBs, possibly for a long time. Therefore, the residual life of the TDBs needs to be taken into account.

(ii) Operator/maintenance error

This class of error includes:

- Input power switched off during operation
- Cables disconnected during operation
- Accidental cutting of cables during operation
- Incorrect installation of TDBs

(iii) Sabotage

Intentional damage to the AMB by cutting cables, damaging windings or sensors, or disrupting operation of the controller.

2) Transportation duty

This section will address whether the TDBs need to provide a support to the rotor during transportation between sites in the instance where the rotor is not locked by other means. References to appropriate ISO shock and vibration standards will be provided.

3) Failure modes

(a) General

The TDBs must survive the contact event without failure. Examples of direct or subsequent failure mechanisms which might occur are:

- Accumulated wear due to normal TDB operation leading to subsequent failure
- Yielding due to excessive load
- Fatigue due to excessive stress cycles
- Excessive temperature resulting in welding or loss of material due to material reaching its melting point.
- Excessive temperature resulting in a change of material properties (ie heat treatment) leading to subsequent failure
- Wear due to contamination or lubrication failure
- Corrosion
- Seizure due to thermal growth and loss of clearance
- Loss of landing sleeve interference fit
- Damage to a compliant mount
- Undetected contact leading to subsequent failure

Other failure modes which can be eliminated by design are associated with stress limits in both the rotor and stator parts. The design must ensure that all parts are below yield at the maximum specified load as determined by rigorous rotor dynamics analysis. The rotor parts must also consider the shrink fit with which they are likely to be fitted to the shaft together with the stress cycling associated with each machine start/stop cycle. Inadequate design could lead to low cycle fatigue failure.

Corrosive contaminants and the associated pH level must be factored in at the design stage; otherwise they may lead to premature failure due to stress corrosion cracking. The use of qualified materials is required in such environments.

Chemical contaminants such as hydrogen or mercury that may lead to embrittlement limit the choice of available materials for the rotor.

Failure mechanisms specific to each type of TDB are identified in the following sections.

(b) Rolling element specific

Rolling element bearings for conventional applications in passive rotating machines are well-understood in terms of their failure mechanisms. However, for use as TDBs in AMB systems, the following failure mechanisms require special consideration:

- Windmilling
- Fretting
- Brinneling
- Skidding
- Cage failure

(c) Sliding bearing specific

The primary failure mode for sliding bearing type TDBs is wear of the dry lubricated bush material, which occurs during each contact event. Eventually after a defined number of contact events the clearance in the TDBs exceeds a pre-defined limit which is necessary to protect the other clearances within the machine. In normal touchdown service this wear is predictable and repeatable and can be remotely inspected by performing a clearance check.

The amount of wear during each contact event will depend on the load, the margin associated with the material peak surface temperature and the duration of the contact. The last two of these depend on the braking available to bring the rotor to zero speed (e.g.: aerodynamic load, regenerative braking). The peak surface temperature will also depend on the load and the design of both the stator and rotor parts of the TDB.

Aggressively abrasive contaminants such as sand may be tolerated if appropriate material selections are made, but they must also be factored into the design, otherwise excessive wear of the pad material and/or damage to the rotor sleeve may occur during a contact.

4) Environmental factors

In particular cases, there may be significant issues relating to the nature of the processes. These include:

- Corrosion resistance
- Particulate contamination
- Liquid contamination
- Operating temperature
- Available cooling flow

5) Rotordynamic modelling considerations

This section will outline rotor and casing modelling requirements to provide a system model adequate for TDB performance and life estimation. The rotor dynamic simulation must provide predictions of motion and force at the TDBs, which can be used as requirements for the TDB design. The simulations must also provide predictions of relative rotor-stator response sufficient to evaluate potential contact or excess motion at axial locations other than the TDB. Localized rotor compliance may be missed by modally reduced models, leading to inadequate fidelity for such predictions.

6) Contact classification/severity

With respect to the duration of contact, the following cases require consideration.

(a) Momentary contact

In this scenario, the AMBs quickly re-center the shaft after a large excursion. Following a momentary contact the system returns into normal operation and typically no trip signal is issued. A momentary contact is typically triggered by a short overload of the AMBs, for example, following compressor surge.

Although the contact time is short it must not be neglected since races and balls of rolling element TDBs suffer from impact load and high acceleration rates. The strains of these components are proportional to the speed difference between rotor and races before the impact.

The AMB control system should increase a momentary contact counter depending on the rotation speed of the shaft. Several consecutive momentary contact events shall be counted separately.

(b) Longer duration contact

If the contact lasts longer than that assessed for (i) above, it is considered as a drop/coast down. The shaft may exhibit different orbit responses such as pendulum (rocking) vibration, combined rub and bouncing and full rub (backward or forward whirling). The control system should be able to detect the orbit response and provide counters for response types as appropriate. The counters should take into account duration of contact, shaft speed, whirl frequency and direction of whirl (forward or backward). Simpler implementations such as just counting the number of events, independent of the rotation speed, may be applied, including:

- Rocking
- Bouncing
- Forward whirl
- Backward whirl

Forward whirl is precession of the rotor in the same direction as rotor spin. Backward whirl is precession of the rotor in a direction opposite to that of the rotor spin.

7) Control actions following TDB contact

(a) AMB controller action

There are options to use the available AMB force capacity to apply control action to the rotor during and after TDB contact. This includes:

- Recovery of controlled levitation within a pre-set time window
- Unsuccessful recovery within a pre-set time, leading to:
  - Modification of control and attempt to recover levitation
  - Delevitation followed by relevitation after a pre-set time delay or lower speed
  - Attempt to recover levitation and issue ESD (emergency shutdown)
  - Delevitate and issue ESD request
- Modify or suppress alarm/trip for known events (expected impulse, etc.)

(b) Plant/Variable Frequency Drive (VFD) control actions

In specific applications, one or more of the following scenarios may apply during spin down and affect rundown speed versus time:

- Rundown with compressor braking (consider lowest power scenario)
- Rundown with regeneration/resistive brake and anti-surge valve open
- Rundown with compressor braking and regeneration/resistive braking
- Rundown with regeneration/resistive braking
- Rundown with mechanical braking
- Steam/turbine generator scenarios
- Coast down

8) Design considerations for soft mounts, friction, whirl frequency reduction and whirl energy dissipation

(a) Motivation for using soft mounts

When a rotor drops onto the TDBs, the mechanical bearing (rolling element or bushing) will typically provide relatively little damping. This means that rotor response as it runs down through various rotor/structural resonances may be very high. Consequently, there is a desire to provide a damping mechanism associated with the TDB and this is most readily and most commonly accomplished by adding compliance to the TDB by soft mounting it.

(b) Design tradeoffs

The principle design tradeoff associated with soft mounting TDBs arises because a very soft mount will permit a high level of damping, but will also allow large excursions of the rotor during the touch-down event. Consequently, making the mount softer requires reducing the TDB clearance in order to ensure that the total displacement (clearance plus soft mount deflection) is small enough to still protect the machine. A good design achieves an acceptable balance between damping and amount of rotor free motion prior to TDB contact.

(c) Friction

Friction applied to the rotor by the TDB, which tends to slow the spin of the rotor, will tend to induce rolling of the rotor in the TDB clearance. This rolling is a form of backward whirl and is generally undesirable.

(d) Forward whirl

Forward whirl is generally induced by mass unbalance on the rotor although it may also be induced by aerodynamic cross-coupling. It is very hard to produce fully developed forward whirl in the clearance of the TDB (“fully developed” means that the radius of whirl equals the TDB clearance).

(e) Backward whirl

Backward whirl is generally induced by rotor-stator friction although it may also be induced by aerodynamic cross-coupling. Fully developed backward whirl in the clearance of the TDB involves very large contact forces at the TDBs with a very high potential for rotor damage, so it needs to be avoided.

F. *TDB Design Process*

The TDB design must take into account the nature and duration of the loads that will be imposed during service. Traditionally, the design requirement has been that the TDBs must survive a specific number of five-axis drops and spin down from full speed and full load. However, the TDBs often see service under different circumstances, based on the trigger events. This additional service of the TDBs must be included in design analysis. Clearly, this is a complex issue to be resolved by Part 5 of the standard. Figure 3 provides an indication of the design process flow logic.

G. *Conclusions*

This paper has outlined some of the complex issues that must be overcome in order that an international standard may be established for AMB levitated rotors with integrated TDBs. The complexity arises from the multi-functional requirements that must be accounted for in the system design process. Although not presented in this paper, the design process will also include experimental tests to calibrate models that may be required for design verification.

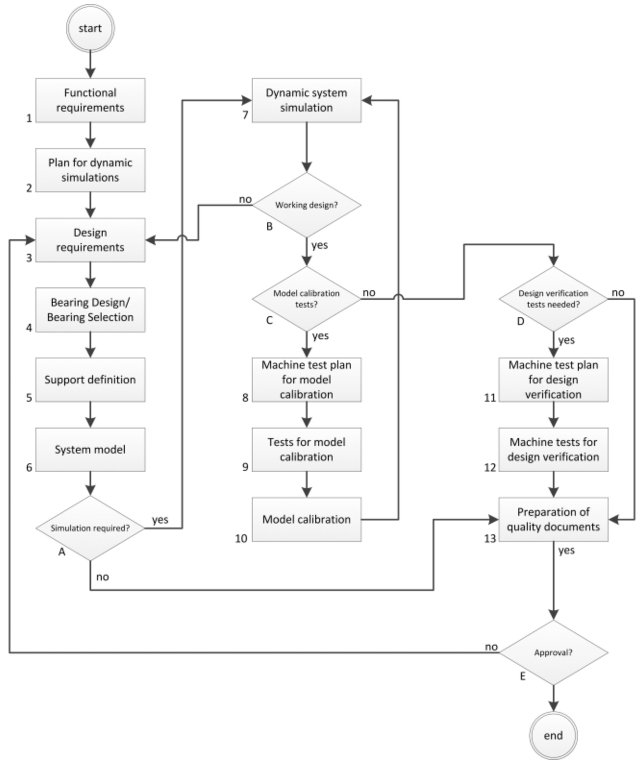

Figure 3. TDB design process flow diagram.

REFERENCES

[1] ISO 14839-1:2002 Mechanical vibration -- Vibration of rotating machinery equipped with active magnetic bearings -- Part 1: Vocabulary.

[2] ISO 14839-2:2004 Mechanical vibration -- Vibration of rotating machinery equipped with active magnetic bearings -- Part 2: Evaluation of vibration.

[3] ISO 14839-3:2006 Mechanical vibration -- Vibration of rotating machinery equipped with active magnetic bearings -- Part 3: Evaluation of stability margin.

[4] ISO 14839-4:2012 Mechanical vibration -- Vibration of rotating machinery equipped with active magnetic bearings -- Part 4: Technical guidelines.

[5] Magnetic Bearings Theory, Design, and Application to Rotating Machinery, Editors: Schweitzer, Gerhard, Maslen, Eric H., Springer, 2009.

[6] J. Schmied, and J. C. Pradetto, “Behavior of a one ton rotor being dropped into auxiliary bearings,” *Proceedings of the 3rd Int. Symp. on Magnetic Bearings*, pp. 145-156, 1992.

[7] R. G. Kirk, and T. Ishii, “Transient response drop analysis of rotors following magnetic bearing power outage,” *Proceedings of MAG'93*, pp. 53-61, 1993

[8] R. G. Kirk, E. E. Swanson, F. H. Kavarana, and X. Wang, “Rotor drop test stand for amb rotating machinery, Part 1: description of test stand and initial results,” *Proceedings of the 4th Int. Symp. on Magnetic Bearings*, pp. 207- 212, 1994.

[9] E. E. Swanson, R. G. Kirk, and J. Wang, “AMB rotor drop initial transient on ball and solid bearings,” *Proceedings of MAG'95*, pp. 207-216, 1995.

[10] L. Hawkins, A. Filatov, S. Imani, and D. Prosser, “Test results and analytical predictions for rotor drop testing of an active magnetic bearing expander/generator,” *ASME J. Engineering for Gas Turbines and Power*, vol.129, pp. 522-529, 2007.

[11] J. Denk, B.-E. Köhler, G. Siegl, and P. Siebke, “Landing tests with a 6300rpm, 9t AMB rotor in rolling element back-up bearings,” *Proceedings of the 14th Int. Symp. on Magnetic Bearings*, 2014.

[12] P. Siebke, and H. Golbach, “A novel rolling element back-up bearing for a 9 t rotor application,” *Proceedings of the 14th Int. Symp. on Magnetic Bearings*, 2014.

[13] G. Siegl, T. Tzianetopoulou, and J. Denk, “Simulation and experimental validation of a 9 ton AMB rotor landing in rolling element back-up bearings,” *Proceedings of the 14th Int. Symp. on Magnetic Bearings*, 2014.

[14] A. R. Bartha, “Dry friction induced backward whirl: theory and experiment,” *Proceedings of the 5th IFToMM Conference on Rotor Dynamics*, 1988.

[15] M. Fumagalli, P. Varadi, and G. Schweitzer, “Impact dynamics of high speed rotors in retainer bearings and measurement concepts,” *Proceedings of the 4th Int. Symp. on Magnetic Bearings*, 1994.

[16] W. C. Foiles, and P. E. Allaire, “Nonlinear transient modeling of active magnetic bearing rotors during rotor drop on auxiliary bearings,” *Proceedings of MAG'97*, 1997.

[17] G. Sun, A. B. Palazzolo, A. Provenza, and G. Montague, “Detailed ball bearing model for magnetic suspension auxiliary service,” *Journal of Sound and Vibration*, vol. 269, pp. 933-963, 2004

[18] J. Anders, P. Leslie, and M. L-E. Stacke, “Rotor drop simulations and validation with focus on internal contact mechanisms of hybrid ball bearings,” Paper GT2013-95816, *ASME/IGTI Turbo Expo*, 2013.

[19] S. Lahriri, and I. F. Santos, “Theoretical modelling, analysis and validation of the shaft motion and dynamic forces during rotor–stator contact,” *Journal of Sound and Vibration*, vol. 332, pp. 6359-6376, 2013.

[20] J. J. Janse van Rensburg, C. Vanek, and *F.* Worlitz, “Backup bearing modelling for turbo machines with high axial and radial loads,” *Proceedings of the 14th Int. Symp. on Magnetic Bearings*, 2014.

[21] A. Kärkkäinen, M. Helfert, B. Aeschlimann, and A. Mikkola, “Dynamic analysis of rotor system with misaligned retainer bearings,” *ASME Journal of Tribology*, vol. 130, pp. 021102, 2008.

[22] C. Jarroux, J. Mahfoud, R. Dufour, B. Defoy, and T. Alban, “On the dynamics of rotating machinery supported by AMB during base motion,” *Proceedings of the 15th Int. Symp. on Magnetic Bearings*, 2016.

[23] R. Jayawant and A. Masala, “Design and commissioning of a 3.3 MW motor-driven compressor fully supported on active magnetic bearings,” *Proceedings of the 15th Int. Symp. on Magnetic Bearings*, 2016.

[24] L. Ginzinger, and H. Ulbrich, “Control of a rubbing rotor using an active auxiliary bearing,” *Journal of Mechanical Science and Technology*, vol. 21, pp. 851–854, 2007.

[25] P. S. Keogh, M. N. Sahinkaya, C. R. Burrows, and I. S. Cade, “Rotor/auxiliary bearing dynamic contact modes in magnetic bearing systems,” *Journal of the Japan Society of Applied Electromagnetics and Mechanics.* vol. 16, pp. 266-271, 2008.