Field Experience with Automated Tools in Both Remote and Local Commissioning of Active Magnetic Bearing Systems.

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***Abstract*—This paper describes field experience with 3rd generation AMB automated commissioning tools. This covers experience on "first of class" machinery on sites where both AMB specialists were present using the automated commissioning tools and other installations where no AMB specialist was present and all commissioning was conducted by remote guidance of local non-specialist staff and remote use of automated commissioning tools.**

I. INTRODUCTION

A. Automated Commissioning Tools

Automated commissioning tools, also known as 3rd generation magnetic bearing functionality [1], offer the potential for increased industrial acceptance of magnetic bearing systems due to a number of significant advantages:

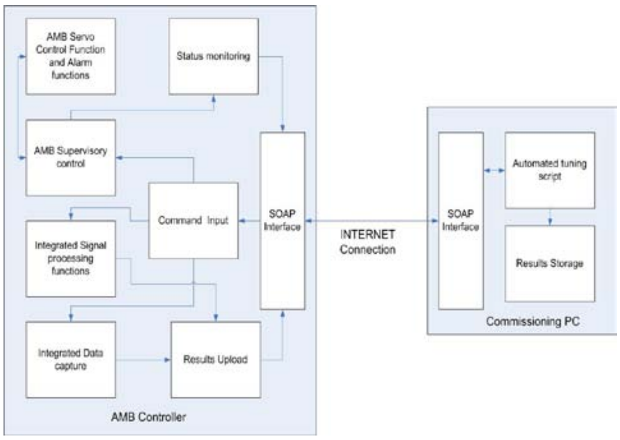
- They lower the level of skill and training required to execute the commissioning process;
- They transfer commissioning activities to OEM and end user non-specialist engineers;
- They reduce the time required for commissioning;
- They improve the consistency and repeatability of commissioning measurements and record keeping.

Automated commissioning covers not only the processes traditionally associated with "automatic tuning" (ie configuration of the dynamic parameters of the AMB controller), but also the automation of the more "nuts and bolts" aspects of the commissioning process including such items as verification of mechanical build.

The automated commissioning tools, and in particular, automated tuning, use a network connection to link the "signal processing" functions integrated within the AMB controller with more capable analysis software running on an external computer. This external software can change parameters in the bearing controller to modify controller configuration, set up measurements, control data collection and apply results.

The tools discussed in this paper are written in MATLAB which provides advanced data processing and display within a general purpose programming environment including networking. For distribution of the tools, the MATLAB code is compiled to an easily distributed executable program. The architecture of the automated commissioning tools is described in [2]. Figure 1 shows the architecture of the system.

Figure 1 – Automated commissioning framework



Automated commissioning works in parallel with the existing browser based AMB display system. The display system remains connected over the same network connection as the automatic commissioning tools and provides additional opportunities to monitor the commissioning progress. For remote commissioning it is occasionally helpful to exchange digital photographs of the bearing installation or arrange a video conference with a mobile camera to examine more details.

B. Test Installations

Results of automated commissioning on two active magnetic bearing (AMB) installations are presented in this paper. Both installations involved "first of class" applications and included both:

- Applications where commissioning was conducted on site by an AMB specialist using the automated commissioning tools.
- Applications which were commissioned remotely (in a separate continent) where no AMB trained specialist travelled to the OEM site and all on site support was provided by general electrical and mechanical technical staff.

The first machine, located in the USA, is a magnetic bearing supported test rig used for testing of fluid film and squeeze film damper bearings. The AMB in the test rig was commissioned under the remote supervision of Waukesha in the UK (WMB) with local support by engineers.

The technical specification of the fluid film test rig is shown in Table 1.

TABLE I. SPECIFICATION OF THE FLUID FILM TEST RIG

Parameter	Value
Rotor Mass	82 Kg
Bearing Span	524 mm
Speed range	0 to 25,000rpm
AMB configuration	2 radial bearings
Controller	Elephanta
Radial bearing load Capacity	18,000 N

The controller used in this application is an Elephanta cabinet customized to control only four axes. There is no AMB axial bearing. The test rig is shown in Figure 2. The magnetic bearing supported rotor is in the grey assembly on the left side of the photo.

Figure 2 – Fluid film bearing test rig

The second installation is a retrofit industrial turbo machine. The unit was pre-assembled with the magnetic bearings (supplied by a different vendor) prior to the arrival on site of the WMB commissioning specialists. For retrofit applications of this type where one is reliant on documentation from a separate vendor, the verification of the mechanical build and system check-out is of critical importance. The motivation for using the automated commissioning tools in this case was to expedite this verification of the mechanical system integrity.

The technical specification of the turbo-machine AMB's is as shown in table II.

TABLE II. SPECIFICATION OF THE TURBO-MACHINE

Parameter	Value
Rotor Mass	110 Kg
Bearing Span	400 mm
Speed range	0 to 22,000 rpm
AMB configuration	2 radial / 1 axial
Controller	Zephyr
Radial Bearing load capacity	5700 N
Axial bearing load Capacity	22,000 N

The controller used in this application is a custom Zephyr unit. This was fitted with an up-rated amplifier for the axial axis to allow a maximum current of 60A rather than the normal 27A. This current rating is at the standard Zephyr DC link voltage of 390V giving a per amplifier VA rating of 23.4 kVA. This was necessary to match the controller to the pre-existing magnets and sensors. In order to achieve the higher rating, the controller was modified so that rather than the standard natural convection cooling it was cooled by a forced air flow. The process of up-rating the controller is described in [3]. The controller is shown in Figure 3.

Figure 3 – AMB controller for turbo-machine

II. AUTOMATED-COMMISSIONING TOOLS

A. *Build Verification Tools*

These tools are concerned with the integrity of the mechanical build of the equipment and the correctness of the inter-connections between the AMB controller and the equipment. There are simple checks to verify this such as:

- When we attempt to drive current in one magnet, do we get current in the correct magnet?
- When we drive current in one magnet, are we able to move the rotor?
- When we drive current in one magnet, do we see motion in the expected sensor signal?
- When we pull the rotor with the magnets, do we see the expected magnitude of motion?
- Optimization of sensor phase for synchronous sensor demodulation [4]

These are all simple tests, but executing a full set of verification measurements manually is time consuming. For an application where we are retrofitting onto pre-existing AMB hardware from a competing vendor, the potential for misconnection is higher than normal (due to differing terminology / labeling and possible mis-interpretation of drawings). In this case the use of the build verification procedures is necessary and the use of the automated commissioning tools is essential to expedite this process.

The build verification tools used during the commissioning of the 2 units were:

- System check-out scripts
- The de-levitated sensor calibration tools.
- Levitation scripts

- The partially levitated sensor calibration tools.
- The fully levitated scripted clearance check.

The system check-out scripts are used to drive current in each of the magnets in turn, to ensure that it is possible to drive current and that it is applied to the correct winding. This eliminates the manual parameter manipulation (and the possibility of errors) that would normally be performed.

The de-levitated sensor calibration tools are used on the Zephyr controller to set up the phasing of the sensor phase sensitive synchronous de-modulation as described in references [2] and [4]. These tools are also used on both controller types to obtain a rough calibration of the sensor system, including setting up gains and offsets to allow levitation. This calibration can be either against the pre-defined (or measured) clearance in the auxiliary bearings, or against some other external measurement device such as dial gauges.

The levitation scripts support levitating each axis in turn followed by levitating each bearing in turn prior to levitation of the complete rotor. This eliminates the manual parameter manipulation (and the possibility of errors) that would normally be performed to achieve this process. The initial suspension is typically performed using a low-stiffness, low-bandwidth tuning configuration.

The partially levitated sensor calibration tools allow the rotor to be levitated on all axes (or planes) except one, and then the currents in the non-levitated axis (or plane) are manipulated to pull the rotor around within the auxiliary bearing clearance. This allows rapid evaluation of correct centering and calibration of the sensor system. The complexity of this parameter manipulation means that it is very difficult do this manually. Automated tools enable this capability.

The fully levitated scripted clearance check, replicates the functionality of the traditional AMB clearance check, where manipulation of the reference position is used to traverse the rotor within the auxiliary bearing clearance and current inflexion points and divergence between the actual and reference positions are used to determine contact points. This type of automatic functionality has been available within the Elephanta controller for many years, but bringing it into the external tools allows for several improvements:

- The functionality is available on all controllers with a consistent interface
- Faster measurement time (see below)
- Better graphical display and data recording

Due to the configuration of the integral loops within the MIMO controller architecture, the traditional clearance check is quite slow, with each measurement point requiring the integral loop to settle before making the associated measurements. With the external automated commissioning tools, rather than manipulating the reference positions, it is feasible to manipulate the offset in the sensor calibration block, with the automated tools keeping track of the "effective reference position". This eliminates the settling time associated with the integral loops and leads to faster measurements.

The use of the external tools also allow for more easy customization of such items as the step sizes, number of measurements at each position (which are then averaged) and measurements required to confirm an inflexion – all of which allows for faster (optimal) measurements.

Details of several of the algorithms are given in reference [2].

B. *Dynamic tuning tools*

These tools are concerned with configuring the dynamics of the AMB controller. The typical processes required in setting up the dynamics of the system includes:

- Configuration of flux estimators
- Amplifier bandwidth optimization
- Open loop transfer function tuning.
- Spectral measurements

The use of automated commissioning tools (for both dynamic tuning and system check-out), results in faster measurement times and greater consistency and repeatability of measurements, and reduces potential for human error in the set up of measurements.

III. RESULTS

A. *Fluid Film Bearing Test Rig*

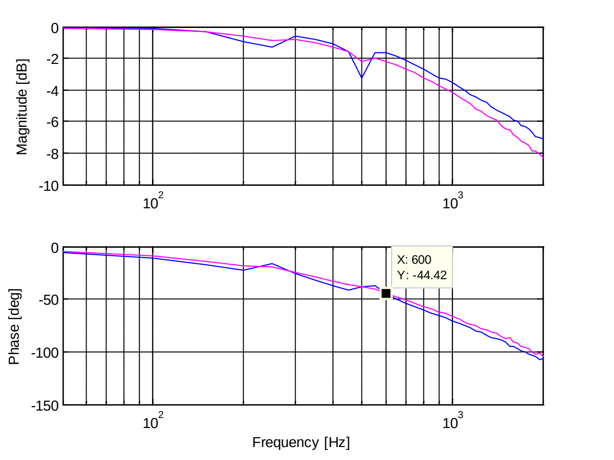
The fluid film bearing test rig is located in the USA. It was commissioned remotely from England by magnetic bearing commissioning engineers. Local staff, none of whom have magnetic bearing experience, installed the magnet bearings, made all the electrical connections and took measurements as required by for the automated commissioning tools. The tools used for remote commission of this AMB are:

- System check-out scripts
- Amplifier bandwidth optimization
- De-levitated sensor calibration tools
- Levitation scripts
- Spectral measurements
- Partially levitated sensor calibration tools
- The fully levitated scripted clearance check
- Open loop transfer function tuning

The system check-out scripts and initial calibration were used by the remote engineers with a network connection to the bearing controller and a local non-specialist engineer on hand to take current and dial gauge measurements. The current checks took 50 minutes. This time was dominated by the time for the levitation and de-levitation sequence. We discuss below how this delay can be eliminated with a special commissioning state for system check-out. The position checks and initial calibration took a similar time. Traditionally, these checks would have required a visit to site by a magnetic bearing commissioning engineer, but this project has demonstrated that these checks can be conducted remotely.

Having confirmed that the power and magnet connections are correct, the next step in the commissioning process is to tune the bandwidth of the amplifier and magnet circuit to a target determined by rotor dynamic analysis. The automated commissioning tools measure and tune this bandwidth using the transfer function capability built into the Elephanta controller. For the fluid film test rig, this was done remotely in 30 minutes for all axes, without needing local support. Without automated commissioning, this activity takes several hours. The automated commissioning tools also tune the parameters for a flux estimator used to control flux rather than current for better dynamic performance. Figure 4 shows the tuned amplifier bandwidth for both magnets of one axis of the test rig.

Figure 4 – Amplifier bandwidth, -45° deg @ 600Hz



Next, the levitation script was used by the remote engineer to levitate and fine tune each axis in turn using initial calibration and loop shaping schemes from rotor dynamic analysis. The goal of this step is to achieve a soft suspension to allow better centering of the rotor. For this machine, we used remote manual adjustment of the controller terms to stabilize the suspension, but as discussed below, we plan to automate the heuristics used manually to achieve a stable suspension.

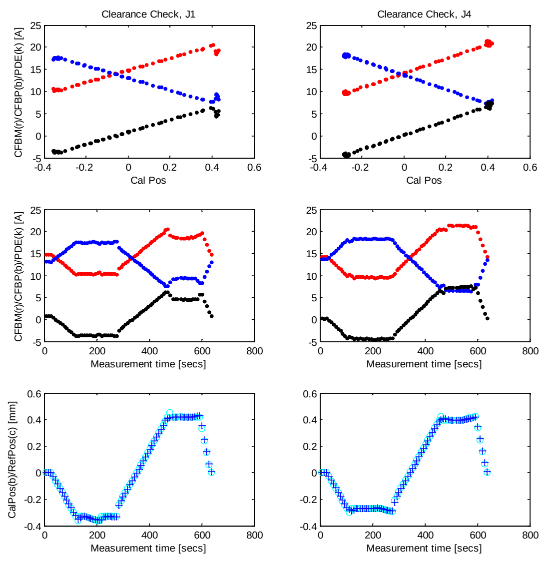
When the initial suspension was achieved, it was clear both audibly (though a telephone link to the bearing site) and from a remote display of bearing vibration level, that the suspension was very noisy. An exchange of digital photographs and a video review identified corrections to cable screening and to cable routing (to separate magnet cables from the same ducting as flux feedback sense wires). After the local engineers completed this work, the levitation tool was run remotely again to achieve a much quieter suspension.

The spectral measurement tool was used to measure the noise levels with no current flowing, with only bias current in each magnet and when suspended. This complete set of measurements takes approximately 20 minutes using the spectral measurement tool, compared with 2 hours required to take the measurements manually, due to all the changes to parameter settings required. The tool also ensures that all results are captured and saved in a consistent manner.

With a soft suspension, the partly levitated calibration tool was used to improve the position sensor calibration. The remote engineer ran the tool and the local engineers used a dial gauge to measure movement of the rotor. It took 11 minutes to calibrate all four axes using planar movement. This calibration procedure also revealed that one sensor was using a distinctly different portion of its electrical range to all the others, suggesting a possible build issue with the machine.

With a soft suspension and improved sensor gain calibration, the scripted clearance check was used to verify the design clearances and set the sensor offsets to center the rotor. Figure 5 shows the display generated during the J1-J4 parallel traverse clearance check. The top two traces show current against offset. The middle traces show current against measurement time and the bottom two traces show position against time. It is clear from the traces that J1 is better centered than J4. The 12 minutes required for this scripted clearance check is at least five times faster than the existing clearance check algorithm built into the controller.

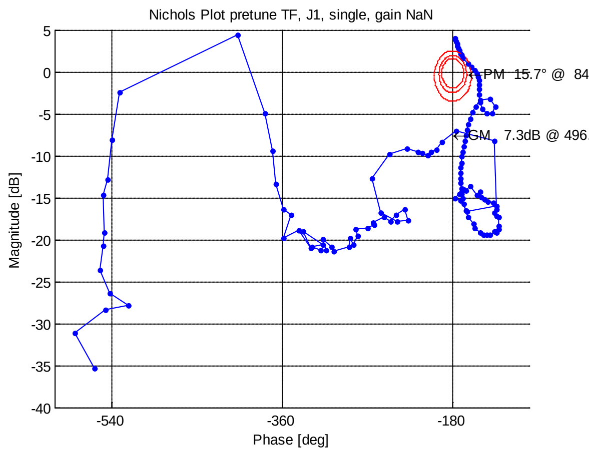
Figure 5 – Scripted clearance check



With an initial levitation and well centered rotor, it is possible to use the open loop transfer function tuning tool to measure and improve the stiffness and check the stability of suspension across the modes of the rotor. The Elephanta controller has a built in transfer function measurement capability, but this provides limited control over disturbance level, frequency step size and averaging of the measurement data. The open loop transfer function tool sequences a number of built in measurements then combines the results into a single transfer function measurement (together with a coherence estimate for the overall measurement). Combining measurements in this way allows us to use a reduced disturbance at low and critical frequencies to avoid destabilizing the suspension. It also allows closer frequency spacing near rotor modes and increased averaging where the response is low to improve the coherence of the measurement.

Figure 6 shows an intermediate result of one such transfer function measurement as a Nichols plot. The red rings demark the sensitivity zones defined in ISO-14389 [5]. It is clear that the system shown in the figure needs further tuning to stay in zone A at all frequencies (i.e. outside the outer red ring). This was resolved by adjustment of controller gain.

Figure 6 – Open loop transfer function



B. Industrial Turbo-machine

The turbo-machine was commissioned with the original AMB mechanical hardware together with a new Zephyr controller. The commissioning was conducted using an on-site commissioning presence. The Automated Commissioning tools used during this process were:

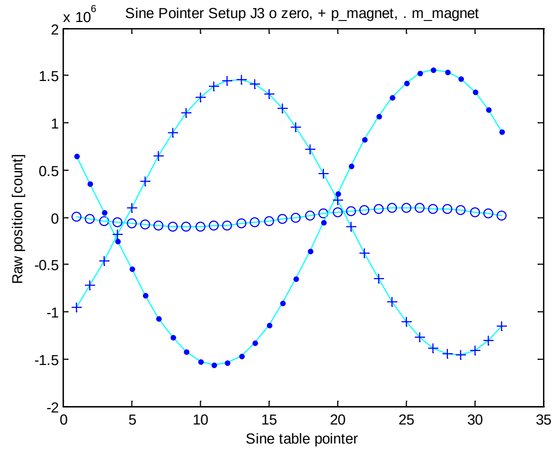
- The System check-out scripts
- The de-levitated sensor calibration tools.
- Levitation scripts
- The partially levitated sensor calibration tools.
- The fully levitated clearance check and calibration tools.

The system check-out scripts were used to drive current in each of the magnets in turn (remembering that these were the windings of the original bearing). Total time for execution of this script across all axes was 28 minutes, with no abnormal issues being identified. This compares favorably with the 120 minutes which this exercise would take when executed manually by a commissioning engineer.

A modification to the state machine of the AMB supervisory control system was identified which would allow this to be further speeded up. This change involves the creation of a commissioning state which would allow the direct enabling of individual axes (and/or amplifiers) without the need to undergo the normal full levitation sequence. This change is described in the review of further work.

The de-levitated sensor calibration tools were used to set up the phasing of the sensors (remembering that these were the sensors of the original bearing). These tools were also used to obtain a rough calibration of the sensor system. Time for execution of the sensor phasing on all 5 axes was 55 minutes compared to a typical time to execute this manually of 90 minutes. The phasing plots for one axis are shown in Figure 7.

Figure 7 – Sensor phasing



This figure also shows that the sensor has good sensitivity without risk of saturation. Time for the de-levitated sensor calibration (which was performed using dial gauges) was 24 minutes for the 5 individual axes and 9 minutes for the 2 radial bearing planes.

The initial levitation tools are a framework to guide the levitation process before the full verification of the build integrity has been completed. With this application being a retro-fit using another vendor's mechanical hardware, some manual manipulation of the AMB controller gains was necessary to establish levitation. Consequently the time taken to execute the levitation script was 14 minutes. The majority of this time was spent in adjustment of the controller gains as described above. One of the items for further work is to fully automate the process of initial levitation, capturing the heuristic algorithms employed by the expert commissioning engineer. This will be important in future retro-fit applications where there may be uncertainty around the mechanical configuration of the parts inside the machine.

The partially levitated sensor calibration tools were used to verify the clearances and sensor calibration. Time for the partially levitated sensor calibration (which was performed using dial gauges) was 17 minutes for the 2 radial bearing planes.

The initial configuration of the fully levitated clearance check tools required 17 minutes per axis to execute. It was identified that some of the configuration parameters were set very conservatively. Modifying the parameters (as identified in Table III) reduced the time required per axis to 3 minutes and the time required for one plane to 5.5 minutes.

TABLE III. PARAMETER CHANGES TO SPEED UP CLEARANCE CHECK

Parameter	Original	Revised	Notes
current noise margin	0.1A	0.03A	Controller averaging to DC current gives good results faster
number of intermediate steps	8	1	No need to suffer the time penalty of lots of little steps

Parameter	Original	Revised	Notes
samples to detect coarse-step inflexion	2	1	Stopping sooner avoids integral windup
samples to detect fine-step inflexion	2	3	More little steps after inflexion eliminates current noise

It was identified that when running a clearance check whilst simultaneously supporting multiple browser windows that the SOAP server response time was being degraded by limitations in the TCP/IP stack of the web server module associated with the Zephyr controller. An alternative web server module with superior processing capabilities has been identified and this is currently being evaluated. It is noted that no such performance limitations have been observed in the TCP/IP stack associated with the Chinook or Elephanta controllers. It is expected that once resolved the speed of the clearance check would improve significantly.

Following the system check-out the machine was tuned using conventional tuning tools. At the time this exercise was conducted, the Zephyr controller did not have the full integrated measurement capability; however, this is currently being added to the controller functionality.

The tuning exercise identified issues with the system:

- The screening of the sensor cables
- Incorrect impeller weights vs. that modeled

The screens on the sensor cables were not connected in the original assembly (identified through increased noise levels when driving current in the associated magnets). This was rectified by connecting the screens in the skid mounted junction box.

The impeller weights differed significantly from the values previously advised and consequently the rotor natural frequencies differed significantly from the values expected. This necessitated a revised tuning structure compatible with the actual rotor-dynamics.

Following resolution of these issues the machine ran to full speed.

IV. CONCLUSIONS AND FURTHER WORK

Automated commissioning has proven to be an effective tool allowing both remote commissioning and making a commissioning engineer more effective when on-site.

To further improve automated commissioning, additional enhancements are under evaluation or being progressed:

- Adding a commissioning state to the AMB controller state machine. In this commissioning state amplifiers (and associated power supplies) are directly enabled, without needing a full de-levitation and levitation sequence. This capability is now being added to all controller types following the testing described here.

- In order to replicate the process undertaken by a skilled commissioning engineer when establishing a soft suspension on a new design of machine, a heuristic algorithm for establishing soft suspension is being investigated.

- Applying more checks to the measured data taken from the controller to warn about excessive noise level, limited use of the working range of the sensor, asymmetry between axes in a journal bearing etc.

- Incorporation of integrated transfer function measurement capability into the Zephyr controller is nearing completion and the deployment of the associated automated commissioning tools will follow.

- Adding a schedule of operations for an engineer to complete prior to the system check-out script including visual and photographic checks to guide a no specialist through the preparatory checks normally conducted by a magnetic bearing commissioning engineer.

- Evaluation of alternate web server modules on the Zephyr controller which offer a more robust TCP/IP stack performance has been completed subsequent to the testing described here. Faster response times will improve measurement like clearance check which control and track movement of the rotor in real time while avoiding integrator wind up. Alternate web server modules will be introduced in the next few months.

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