Integration of Signal Processing Capability in an AMB Controller to Support Remote and Automated Commissioning.

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Abstract

One major limitation to the wide adoption of active magnetic bearings (AMBs) in industry is the time required for commissioning and tuning. In this paper we will report how integration of signal processing capability (especially multi-channel transfer function measurements) within the AMB controller can reduce total commissioning time and especially, the time required on site by a highly skilled AMB specialist.

We also show how PC based automatic commissioning tools make it possible for OEM and end user engineers to commission, tune and maintain AMB machines with only occasional remote support from the AMB vendor and without specialist rotor-dynamic test equipment. Secondary benefits from this approach include increased traceability and repeatability of the tuning process.

The automated commissioning is based on MATLAB scripts and data analysis capabilities. This runs on a separate PC which (via the controller network interface) configures the measurements to be made by the AMB controller. Analysis of the resulting measurements allows automatic modification of controller parameters. These scripts cover several control loops and estimators within the AMB controller including current, flux and position servo control. The robustness and vibration performance are used to assess the resulting control loop. This is based around a concept of dynamic templates which correlate to acceptance criteria according to ISO 14839-2 and ISO 14839-3.

Results from running the automated commissioning process on a high speed test rig are presented. The results show that the dynamic template model provides good control performance with rapid tuning time.

This technology has the potential for the development of sophisticated diagnostic routines which could be activated in the event of anomalous readings, and this further future work is briefly described.

1 Introduction

As magnetic bearings are applied in increasingly remote and inhospitable locations, the need to de-skill the commissioning and tuning process increases (especially for repeat machines). This simplification can be either through allowing remote connectivity or the use of automation in the commissioning process.

Remote connectivity allows an AMB specialist to remotely "hold the hands" of on site technicians or engineers. Automation decreases the need for any involvement from the AMB specialist for the majority of tasks.

In this paper we describe a combination of technologies which when applied together allow for automated commissioning and tuning of magnetic bearing control systems.

2 Overview of the System

The key technology elements which contribute to the automated tuning structure are:

- Commissioning/Tuning scripts. These scripts encapsulate the knowledge and procedures normally followed by an experienced commissioning engineer. The scripts run on a separate PC, which is connected via an internet connection to the AMB controller. The scripts are able to manipulate parameters within the AMB controller and retrieve the resulting data from such actions.
- A Simple Object Access Protocol (SOAP) interface as applied to a magnetic bearing controller. This allows bi-directional data communication between the AMB controller and a separate computer which is able to run "tuning/commissioning scripts"
- Signal processing capabilities integrated within the AMB controller and accessible to the SOAP interface. These include spectral analysis, transfer function analysis and order tracking.
- Other integrated data acquisition capabilities which are accessible to the SOAP interface. These include Trip Data (a high speed capture buffer), Event Log and system status information.
- State behaviour and sequencing within the AMB controller which is accessible (in both read and write modes) to the SOAP interface. This includes the general control sequences of the AMB controller, special states invoked by the SOAP interface, and also special sequences such as the integrated automatic clearance check.

Figure **1** shows a block diagram of the system architecture.

2.1 SOAP Interface

The SOAP (W3C, 2007) interface is supplied in addition to the other existing interfaces of the AMB controller (such as the web server and FTP server interfaces). A variety of Internet protocols could be used for the data transfer, and early versions of this system successfully used FTP as the application protocol. However, SOAP was selected due its widespread use within the Internet developer community, its compatibility with most firewalls and the ready availability of tools on both the Server and Client sides.

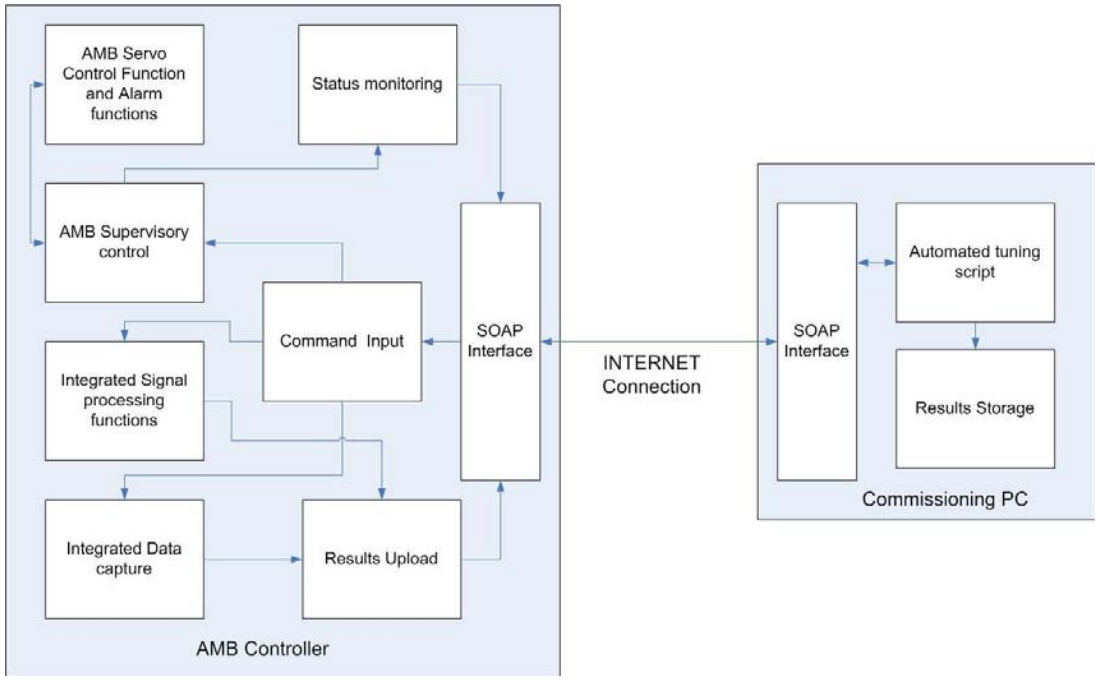


Figure 1 - Architecture of the Automatic Commissioning System

SOAP is a lightweight protocol intended for exchanging structured information in a decentralized environment. By using XML technology it provides an extensible message framework, which allows messages to be exchanged over a variety of underlying application protocols (such as HTTP or SHTTP).

Many of the advanced features normally included in messaging protocols (such as security, reliability etc) are not included within the SOAP protocol, since they are expected to be included in the underlying protocol layers. This lightweight approach gives rise to a protocol which has language neutrality, platform independence, use of XML standards and an ability to pass through firewalls because it piggy-backs the HTTP/HTTPS protocols which just about all firewalls are open to.

The services implemented so far in the SOAP interface are:

Table 1 - SOAP Services Available to The Commissioning Scripts

Command	Function
getParamValueByName	Return the value of a named parameter
setParamValueByName	Set the value of a named parameter to a defined value
getParamValuesByName	Return the values of a list of named parameters
setParamValuesByName	Sets the values of a list of named parameters
getParamNamesByConfig	Returns a list of the parameter names for a given folder path name.
getFileSize	Returns the size in bytes of a named file.
getFileContents	Returns the contents of an ASCII file
getFileContentsBase64	Returns the contents of a file with Binary content
sendCommand	Allows command strings to be passed to the controller
getParamFile	Retrieve the current parameter file from the controller

The system is configured such that all data exchanges are initiated by the PC running the automated tuning scripts. The web server within the AMB controller will respond either by accepting the received command data or by responding with the requested results/status data.

2.2 Signal Processing Capabilities

In order to achieve a robust tuning on an AMB system, extensive dynamic measurements are required. These are made either using external dynamic signal analyzers or special high speed data connections to external system identification tools. In order to avoid the need for such external equipment and in order to work within the data bandwidths likely to be available in a typical site connection, the AMB controller has built in signal processing functions which provide their results as data files which can be accessed through the normal file system of the AMB controller. Since they are normal files, these results can be accessed by the SOAP interface. This on-board processing reduces the volume of data which must be transferred between the controller and the configuration systems. It also eliminates the need for the shipment of expensive (and often bulky) external instruments to site.

The Spectrum Analysis function within the AMB controller allows 2 independent channels to be viewed in the frequency domain. The FFT sample rate can be up to 10KHz with the FFT size from 256 to 4096 points. This gives a maximum span of 5KHz and a minimum span of 125Hz. The resulting waveforms can be averaged in the frequency domain to improve the noise levels. The signal sources can be from a variety of signals within the controller including Position, Current, Flux, Controller Demand signals etc. and these support the measurements required by the automated scripts.

The Transfer Function Analysis within the AMB controller permits 8 channels of swept sine transfer function measurements to be taken simultaneously. The system has 4 independent sources (all at the same frequency) which allows a wide range of excitation to be applied during the transfer function measurement, including single axis, circular (both forwards and backwards), planar, conical and cylindrical (both forwards and backwards) to be applied. This is particularly useful when separation of forward and backwards modes is required. The signals which can be selected for analysis are the same as those which can be analyzed using the spectrum analysis function.

To extract the relevant complex frequency components, the system uses convolution of the measured waveform with the in-phase and quadrature versions of the reference sine wave used for the source (in a similar manner to a conventional lock in amplifier used within an RF signal analyser). The system includes provision for averaging, with increased accuracy being obtained when each measurement point is averaged over a number of cycles. When averaging is applied, then a measurement of coherence can be used to assess the measurement quality.

The Harmonic Capture function provides order tracking (with respect to rotational speed) across 3 orders for all position and current signals within the controller. This uses a similar algorithm to the transfer function analysis to extract the in-phase and quadrature components.

2.3 Commissioning / Tuning scripts

The commissioning scripts run on a separate PC which is connected to the AMB controller via a TCP/IP connection. This separate PC may be located adjacent to the AMB controller or remotely, providing a suitable network connection is available.

The tuning scripts can be written in any language which is able to support a SOAP client interface. In this case we used Matlab (which was then compiled for distribution). Matlab was selected for the data analysis and plotting tools which it supports together with the ability to rapidly develop user friendly display interfaces.

The automated commissioning tool kit comprises a wide range of functions, including: Configuration of the flux estimators within the controller; Tuning of amplifier current / flux feedback loop; System check out and position sensor calibration; Soft suspension; Automatic clearance check; Gain trim of SISO position servo loop based on low frequency gain target; Gain trim of SISO position servo loop based on gain or phase margin; Gain trim of MIMO position servo loop based on low frequency gain target; Gain trim of MIMO position servo loop based on gain or phase margin.

Associated with each implementation of the tuning scripts is a configuration file which allows a full range of parameters to be configured for a particular application. Some of these parameters may be simple and define such items as: host ID, default parameter set, current to lift the rotor, expected position signal range and which axes are co-planar. Other parameters may be more complex, and will be based on prior knowledge (simulation or modeling) of the dynamics of the system together with rule sets for making adjustments to the controller following initial transfer function measurements.

All of the scripts will interact with the controller via the SOAP interface and the progress of the script can be monitored by either observing on the web-server interface of the AMB controller or by observing the log messages presented on the user interface for the script.

The user interface for the script can either be run in an interactive mode with all measurements reviewed by the operator or in a fully automatic mode.

One of the advantages of running the tuning scripts remotely outside of the AMB controller (in addition to the sophisticated analysis capabilities available within the PC environment) is that all measurements are easily archived and there is no concern about long term storage requirements within the embedded system.

In the remainder of this paper we will report on results obtained with the “System check out and position sensor calibration” and “Gain trim of SISO position servo loop based on low frequency gain target” automated scripts.

3 Description of the test rig

The behavior of the automated tuning scripts was tested on a variety of test rigs. The majority of the test work was conducted on the full size test rig located at the Waukesha Worthing facility.

This rig (shown in Figure 2) has a 1.5 Tonne rotor which has a flexible mode at 6700rpm and runs

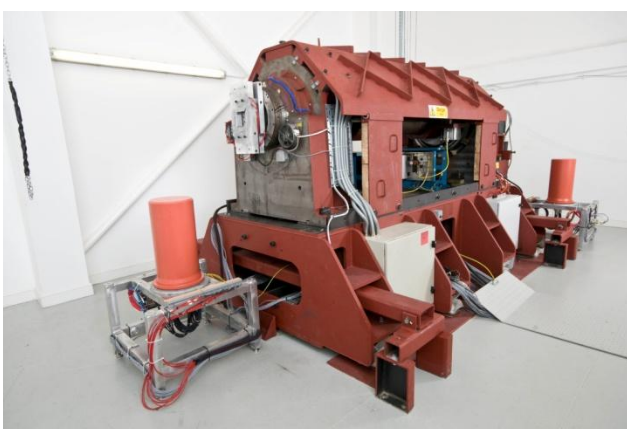


Figure 2 - Large Test Rig

Figure 3 - Small Test Rig

to a maximum speed of 8000rpm.

The control system is a standard Waukesha “Elephanta” AMB controller equipped with the latest software to support the SOAP interface.

A smaller test rig (shown in Figure 3) was used for testing of the system check out and position sensor calibration script. This smaller rig has a 80 Kg rotor which has configurable dynamics and runs to a maximum speed of 12,000 rpm. This smaller rig is equipped with a standard Waukesha "Zephyr" AMB controller equipped with a SOAP server interface.

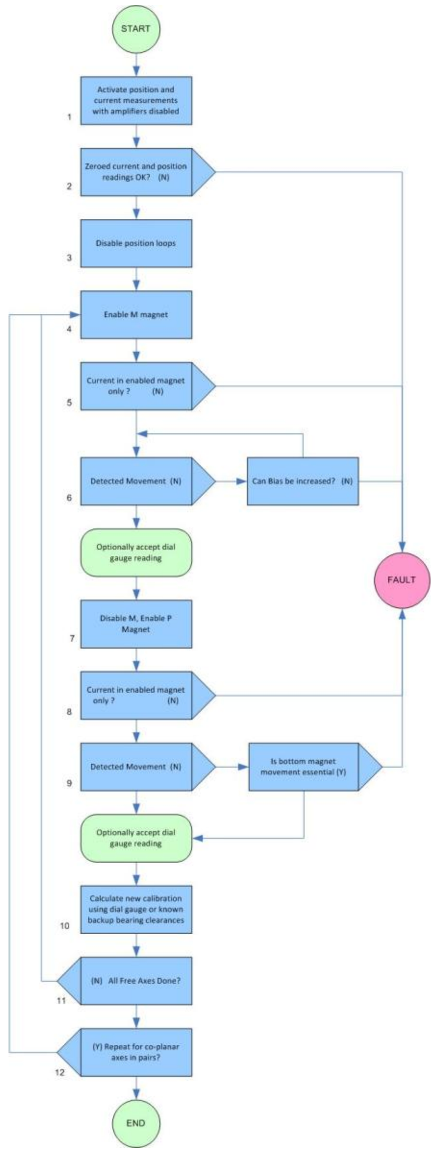


Figure 4 - System Check Out Script

3.1 System Check out and Position Calibration Script

For systems that are built into a customer housing and where the lead out wires for the sensors and magnets are cut to length and wired on site, one of the early commissioning tasks is to verify that all the connections relate to the correct physical orientation of the magnets and sensors, i.e. the bearing and wiring has been correctly installed.

For systems where there are zero (or near zero) clearance abraidable seals or where concentricity requirements on the housings have been relaxed (to reduce cost), it is necessary to ensure that the sensor “zero” position is within the range of physical movement over which the rotor can move before attempting to levitate. Where the shaft ends are accessible, this can be done by physically moving the rotor with jacks or other lifting apparatus. Where the ends of the shaft are not accessible, then it is necessary to pull the rotor by driving current in one magnet at a time.

The system check out and position calibration script is intended to perform these actions and also allow a check on the sensor calibration. The sensor calibration check is particularly relevant where either the sensor modules are individually installed on site or where the demodulation system for an inductive sensor is re-phased to match the final field cables. The sensor calibration part of the script allows for re-calibration of the sensors based on an external reference measurement.

The flow chart for this script is shown in Figure 4. This version of the system check out script is referred to as the “de-levitated system check out script”, since axes (or planes) other than the ones being checked are de-levitated. Where the AMB controller has software configurable phasing of inductive sensor de-modulation, this is incorporated within the script. Alternate versions of the script are available where the rotor is either partially levitated (axes - or planes - other than the one being checked are levitated) or the rotor is fully levitated. These alternate versions are not discussed further here.

3.2 Gain trim of Position servo loop based on QFT and other objectives

The controller structure adopted by Waukesha is a MIMO transfer function matrix with high order capability. Controller co-ordinates are constructed and then individual control loops applied to each co-ordinate. The structure of each loop allows for high order filtering to allow appropriate loop shaping on each controller co-ordinate. This controller structure is particularly well suited to a QFT type analysis (Horowitz, 1993).

A preliminary synthesis of the filters derived from the modeling performed during the rotor dynamic design phase (and as modified by any results from sling testing) are used to obtain a soft suspension.

Once a soft suspension is achieved, the gain of the transfer functions of the individual control loops will be adjusted to ensure that the measured open loop transfer functions meets defined objectives. These objectives are typically defined according to a QFT methodology.

For repeat systems, this gain trimming will normally be sufficient to achieve acceptable system performance. For “first of class” machines, some re-synthesis of the loop shaping filters may be necessary, where the actual dynamics of the machine diverge from the modeling.

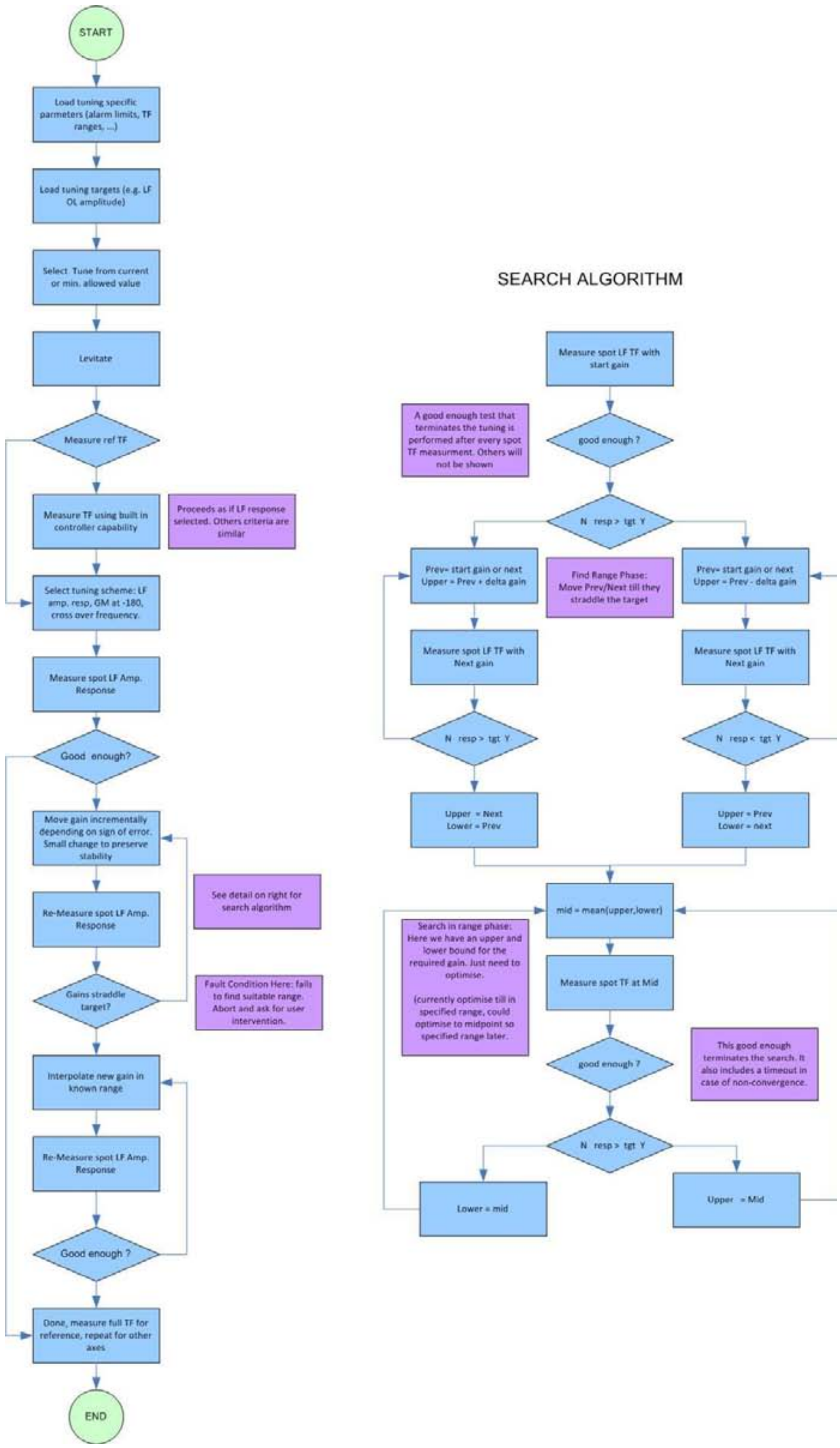
This gain trimming will involve modal excitation within a plane and a measurement of the relevant loop responses. The results are compared against QFT type objectives.

In the results section, we will present results for the script dealing with gain trim of the position servo loop based on low frequency gain target and so we will describe the operation of this script in detail.

Low frequency gain is an important parameter in the robustness of the bearing system to low frequency aero-dynamic disturbance (particularly when operating close to the left hand side of the curve on a compressor/blower), for this reason it is often used as a primary tuning objective with other objectives defined according to a go/no-go criteria. In this case the other go/no-go criteria are compliance with the stability margin criteria according to ISO 14839-3 (International Organisation for standardisation, 2006).

The flow chart for this script is shown in Figure 5. As can been seen in the flow chart, the system will start with a low controller gain and then the script will perform a search (within a permissible range identified in the configuration file) to identify the correct controller gain to achieved the desired low frequency stiffness. The script will then assess compliance with ISO 14839-3 on a go/no-go basis.

Figure 5 - Gain Trimming Script and Search Algorithm



There is quite extensive literature regarding automated methods for performing automatic loop-shaping in QFT using a variety of algorithms. Chait et al. (Chait, Chen, & Hollot, 1999) looked at linear programming methods to execute the search. Chen et al. (Chen, Ballance, & Li, 1998) used genetic algorithms to execute the search. In all of these algorithms the key question is whether the algorithm will converge and if it does converge, will it be to a local minimum in the objective criteria or a global minimum of the objective criteria.

The search algorithm we choose is as follows: Starting with a low controller gain, the transfer function for the target point of interest is measured and then (assuming the transfer function is not already correct) the gain incremented by an amount which is designed to ensure stability. This measurement process is repeated until transfer function measurements which bracket the target are identified. The search then enters a binary search phase where the mid value of gain is measured and the resulting response defines whether the upper or lower portion of the search range should be used for the next binary search. This continues until the target error is below a defined threshold value.

Experience to date has indicated that the algorithm is always convergent with the low frequency stiffness criteria. Convergence with other criteria is not always guaranteed, but inflexion points in the relationship between the objective function and the manipulated variable(s) can be identified by dynamic system modeling or measurement on the "first of class" machine.

4 Experimental results

4.1 System Check Out Script

The de-levitated system check out script was run in interactive mode and the time required for each major function was recorded. With reference to Figure 4 the time taken per axis for the identified groups of steps was as follows:

Table 2 – De-levitated System Check Out Script Timings (per axis)

Steps	Levitation/ De-levitation cycles	Levitation/ De-levitation time [s]	Measurement Time [s]
1 to 6	1	90	5
7 to 11	1	90	5
12	1 (2 per plane)	90	5

As can be seen the total time is dominated by the time taken for the bearing controller to execute its levitation and de-levitation sequences. Further work to adapt the state machine controlling the bearing controller in order to eliminate some of these cycles is proposed.

The repeatability of the system check out script was good, with repeated results reporting clearances (the location to which the rotor was pulled) with a variability of order 2 um.

4.2 Gain trim of Position servo loop based on Low Frequency Stiffness

The gain trim script was tested on the large test rig. Prior to running this script, the Automatic Clearance Check, Flux Estimator Configuration and Amplifier Current Servo loop scripts had been successfully completed. Based on system dynamic modeling, the permitted range for the gain term which was the variable to be manipulated was 19 to 32. The system was initially configured (by the script) with this term at 19 and a stable noise free soft suspension was obtained. Typical final tuned values for the gain term were 24.5.

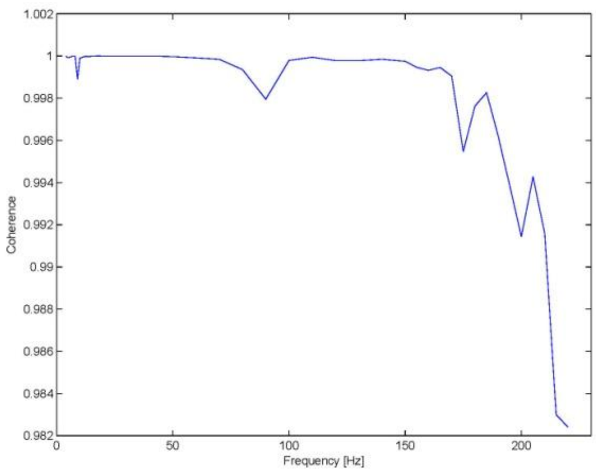
Measurements were configured with the following characteristics:

Table 3 - Measurement configuration

	Band 1	Band 2
Start frequency	3Hz	25Hz
End frequency	23Hz	200Hz
Frequency Step	2	5
Minimum measurement time for each discrete measurement (rounded up to whole number of cycles)	500ms	500ms
Number of discrete measurements at each frequency point	10	10

The minimum coherence for the script to recognize the measurement as valid was 0.96. The achieved coherence was above this level in all cases and the coherence plot from one of the single axis excitations is shown in Figure 6.

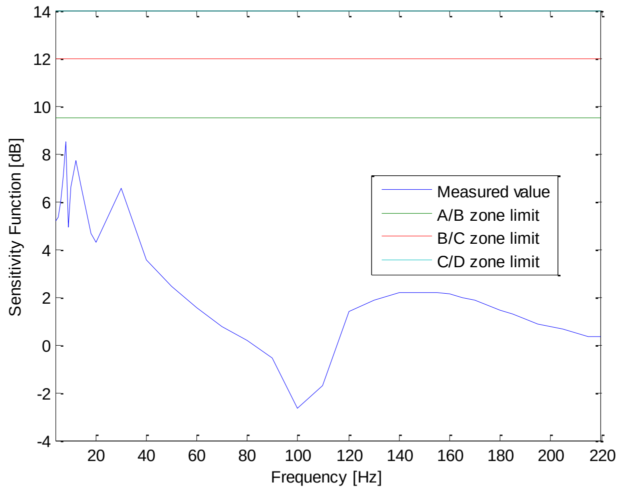
Figure 6 - Typical Coherence Plot



Each initial complete transfer function measurement took 6 minutes to complete. The spot transfer functions then used to trim the gain each required 6 seconds to complete.

The target range for the objective function was 3.85dB to 4dB and the worst case number of iterations was 6 in total (36 seconds), of which 3 were associated with finding the correct sub-range and 3 were associated with the binary search. The actual achieved spread in the objective function was uniformly distributed across the target range. In all cases the system also met the go/no-go critera for compliance with the ISO stability margins. A typical ISO sensitivity plot is shown in Figure 7.

Figure 7 - Typical ISO Sensitivity Plot



In order to assess the convergence of the search algorithm, the objective function was measured for varying values of the manipulated control gain. Figure 8 shows typical transfer functions from these measurements, both for experimental and theoretical measurements. The theoretical modeling differs slightly from the experimental configuration: In the experiment, the manipulated gain was adjusted at one bearing at a time; In the theoretical model the gain was manipulated at both bearings simultaneously. The theoretical results plotted here also include a gain correction factor of 3dB to compensate for a gain change in the software which was not included in the final model. The results show good correlation at lower frequencies, but with some divergence at higher frequencies due to un-modeled system damping in the theoretical predictions.

Figure 8 - Typical Transfer Functions for Varying Controller Gain

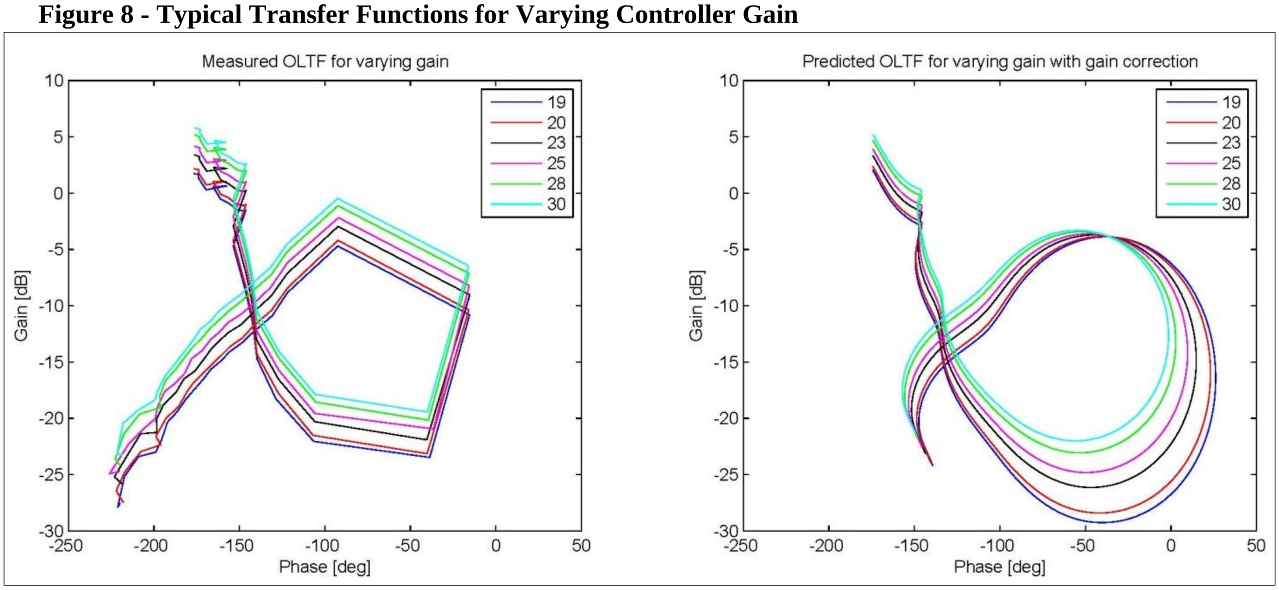


Figure 9 shows the resulting relationship between the manipulated variable and the objective function (both for experiment and from modeling with the gain correction applied). The divergence between the curves is believed to be due to the differences in the way the gains were manipulated in the experimental and theoretical systems (as described above).

Figure 9 - Objective Function (Open Loop Gain) vs Manipulated Gain

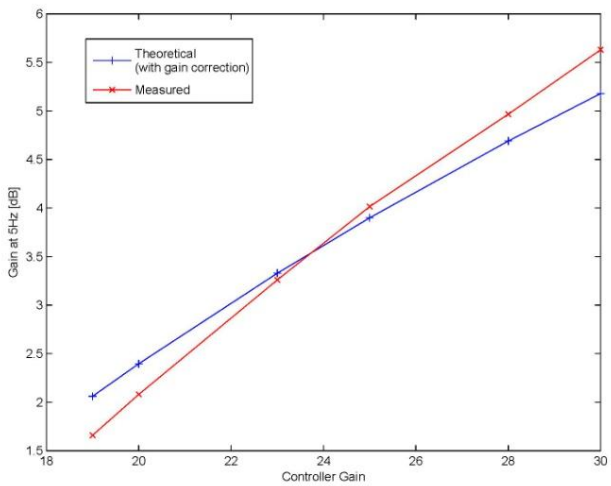


Figure 9 shows that the objective function is monotonic increasing and convergence is guaranteed. The experimental curve is plotted across the full space in which the stable levitation could be achieved and measurements meeting the coherence criteria could be achieved.

5 Conclusions and Future Work

The automatic commissioning scripts have been shown to be an effective method of tuning repeat systems for optimal system gain. Whilst particularly applicable to repeat systems, they are also able to support an experienced commissioning engineer both by allowing the engineer to perform other activities whilst the automated commissioning script is running and by standardizing the execution of the commissioning/tuning process and the associated data recording activities.

The abstraction provided by the SOAP interface allows differing AMB controllers to interface to a set of common script functions.

The times taken for the system check out scripts to execute are dominated by the time required for the levitation and de-levitation sequences on the AMB controller. Further work to develop special sequences within the AMB supervisory controller to allow the scripts to execute with a reduced number of levitation/ de-levitation cycles is being investigated. These sequences will need to maintain compatibility with the sequencing necessary for the safe operation of the power electronics associated with the AMB controller.

5.1 Further scripts to be developed

In addition to the work on the special sequences within the AMB supervisory controller, there is a large body of future work to be undertaken, with the potential for further scripts to be developed. These scripts include:

- Initial levitation
- Configuration of run out compensation
- Configuration of open loop feed forward influence co-efficients
- Configuration and operation of harmonic capture.
- Pre-filter re-synthesis.
- Sophisticated diagnostic routines

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