# Active Magnetic Bearing Control System Testing and Validation using a Multiobjective Genetic Algorithm

I.A. Griffin, A. J. Chipperfield, P .J. Fleming, C. Da vies, N. Grum

*Abstract*— An off-line preliminary assessment of an evolutionary controller testing and validation technique intended for on-line use is described. This approach to closed-loop performance and stability assessment was proposed following a control system design procedure undertaken for the Active Magnetic Bearing rig housed at Rolls-Royce. Derby. Previous control design work for this rig was conducted on-line due to discrepencies between the plant and best available model. The controller validation technique being assessed here employed a multiobjective genetic algorithm to generate various disturbance signals. These disturbances were then applied to a simplified plant model of the AMB rig in order to assess the technique's suitability prior to its use on-line. The closed-loop model is assessed for stability according to it's time responses alone as would happen in the on-line case.

*Keywords*— Active magnetic bearings, multiobjective optimization, genetic algorithms, disturbance testing, stability.

## I. INTRODUCTION

ROLLS-Royce (RR) are currently investigating the feasibility of implementing magnetic suspension technology. Various stages of this feasibility investigation have already been completed [1],[2],[3],[4],[5],[6],[7]. The study has focussed on both model-based and on-line approaches to control design.

One aspect of this investigation is currently focussing on the control of an Active Magnetic Bearing (AMB) pilot plant housed at RR Derby. The pilot plant consists of a vertically mounted rotor and accompanying control system as described in section II. An on-line controller design technique for the AMB rig at RR, Derby was considered necessary due to significant infidelity between this rig and the best available model. Off-line attempts at control algorithm design proved unstable when applied to the plant.

Control of the rotor was initially achieved using a hand-tuned controller [1],[2]. The structure of this controller consisted of P+I control supplemented by lead compensation and a notch filter. This structure was necessary as noise stemming from the D term of a PID con troller had proved problematic and a notch filter tuned to the resonant frequency of the plant was necessary to attenuate vibration. This controller, however, was prone to instability on start-

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up and when subjected to severe disturbances. This behaviour was manifested as uncontrollable oscillation of the rotor journal resulting in repeated impacts with the back-up bearings. The controller was subsequently improved upon using an on-line evolutionary approach to controller design using the hand-tuned controller structure and parameters as the starting point for the optimization [3].

This optimized controller was subjected to a rigorous testing procedure, as described in [3]. This procedure did not, however, address the response of the system to impulse disturbances, a phenomenon known to instigate uncontrollable oscillation or chattering in AMB plant whose bearing stiffness has been set too high [8]. The response of the single acting axial bearing to sinusoidal disturbances also remained undetermined. It was therefore decided that a suitable testing procedure was required to investigate these issues. This paper reports on an off-line assessment of such a testing procedure which was performed using a simplified model of the plant. The closed-loop model of the AMB control system was produced using the Matlab/Sim ulink dynamic system sim ulation environment. The purpose of the assessment was to determine the suitability of the testing procedure prior to applying it to the rig.

The multiobjective genetic algorithm (MOGA) [9] is described in section III. This powerful optimization tool was used to generate parameters for disturbance signals which were then applied to the simplified model of the AMB rig by injecting them between the controller model and the plant model. This was done to simulate the case of disturbances being injected at the power-amp stage of the control loop. (The power-amps are the intended point of disturbance signal injection for the on-line rig assessment. It is hoped that by applying the disturbances to the power-amps, this would best simulate a mechanical disturbance to the rig housing, something which this project is unable to do.)

The MOGA worked towards evolving a disturbance signal for the purpose of causing the maximum difficulty to the control system in terms of increased settling time, more back-up bearing impacts and greater positional errors. The ability of the MOGA to evolve a signal capable of destabilizing the model would then be used to determine the suitability of the testing procedure for on-line application.

## II. THE AMB RIG

Whilst the exercise reported on here w as conducted off-line, the procedure is ultimately intended for use on the

AMB rig at Rolls-Royce, Derby. This plant consists of a large electric pump rotor levitated on active magnetic bearings. The bearing system fitted to the machine provides rotor control in two orthogonal directions radially at the drive end of the pump, two orthogonal directions radially at the non-drive end and one direction vertically (the thrust/axial bearing). Figure 1 shows a schematic of the rotor and indicates the bearing locations.
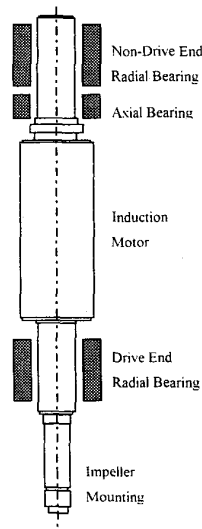
Non-Drive End
Radial Bearing

Axial Bearing

Induction
Motor

Drive End
Radial Bearing

Impeller
Mounting

Figure 1. Schematic of the Rotor.

### A. The Bearing System

Each of the four radial bearing systems consists of a pair of electromagnets mounted one either side of the rotor journal. Position sensors are also mounted on either side of the journal, one pair for each bearing. The analogue voltages produced by each sensor pair are conditioned and the resulting differential voltage is sent to a digital control system described below. The control system processes the incoming sensor data and produces an appropriate analogue output demand signal. This signal is fed to a power amp which, in turn, drives current into the appropriate pair of electromagnets situated on each side of the rotor. Each electromagnet exerts an attractive force on the rotor. The net radial force generated provides levitation at the bearing.

The thrust bearing operates as a single electromagnet mounted vertically above the rotor. As with the radial bearings, the electromagnet produces an attractive force. The attractive upward force of the electromagnet is countered by the rotor's weight acting downwards under gravity. Associated with the thrust bearing are a pair of position sensors and a power amplifier. These are connected to the digital control system and function in the same manner as those associated with the radial bearings.

Whilst this assessmen t exersize was conducted off-line, the testing procedure is ultimately intended for on-line use. The following is a description of the interface facilities as-sociated with the rig. It is these facilities that would enable the MOGA to interact on-line with the hardware described above.

### B. The Hardware Interface

A 100MHz Pentium PC was used in the construction of a complete standalone control system for the AMB rig. The PC was supplemented with a TMS320C40 DSP industry standard card along with an appropriate analogue input/output module. The industry standard DSPlink protocol was used to provide communication between the two cards in the PC.

PENTIUM PC
ISA BUS

ANALOGUE I/O MODULE — DSP LINK — DSP BOARD

ANALOGUE INPUTS

ANALOGUE OUTPUTS

SENSOR PROCESSING CIRCUITRY

POWER AMPLIFIERS

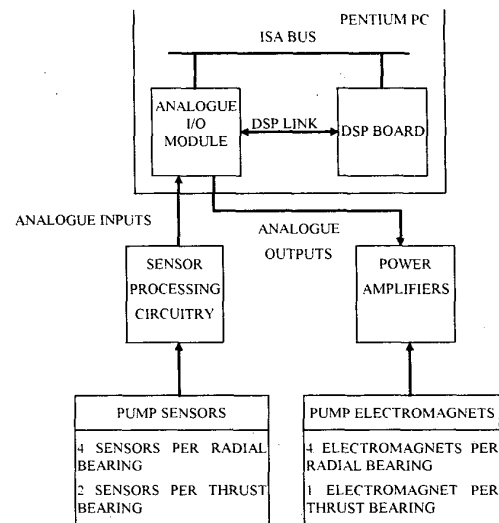| PUMP SENSORS | PUMP ELECTROMAGNETS |
| --- | --- |
| 4 SENSORS PER RADIAL BEARING | 4 ELECTROMAGNETS PER RADIAL BEARING |
| 2 SENSORS PER THRUST BEARING | 1 ELECTROMAGNET PER THRUST BEARING |

Figure 2. Digital Control System.

The architecture and computing power of the TMS320C40 is such that complex control strategies can be implemented. The PC based controller structure is also conducive to implementing high integrity control systems with redundancy management and self-checking features. Figure 3 illustrates the PC based control system described above and the connection of the control system to the application rig. This hardware architecture will provide the system with the capability to control the rig and supply the disturbance signals generated by the MOGA to the power-amps.

### C. The Software Interface

The controller test bed which has been developed and installed on the PC-based digital control system uses industry standard MATLAB/Simulink software development tools extensively throughout. The high level block diagram Simulink package is used for AMB system modelling and simulation work. The test bed parameters produced can then be extraced from the overall system schematic diagram and real-time executable code produced for the controller and disturbance generators through the use of further software tools. This software realisation procedure is illustrated in Figure 3. The interface between Simulink and the hardware located in the PC-based control system is provided by the Rolls-Royce Simulink Rapid Real-Time

Code Generator software. This is achieved by using the MathWorks Real-Time Workshop tool and custom software routines to generate C-code suitable for running on the hardware platform. A Tartan TMS320C40 C/C++ compiler generates executable code for the DSP board. The DSP board is interfaced with the analogue I/O module through the use of a specially written library of Simulink blocks installed on the PC.

The analogue I/O module is configured such that the hardware interrupts which synchronise the analogue to digital sampling functions on the board can also be used to synchronise the Simulink schematic simulation with the actual controller running on the DSP. This provides a fully synchronous design solution which is independent of the DSP code execution time.
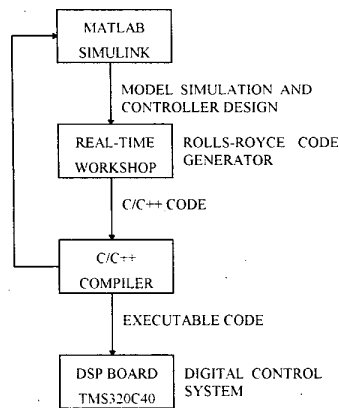


Figure 3. Software Realisation Process

### III. MULTIOBJECTIVE GENETIC ALGORITHMS

The parameters of the disturbance signals used to test for stability were produced using an evolutionary optimization technique. The multiobjective genetic algorithm (MOGA) is implemented using a standard GA [10] with extensions for multiobjective ranking, fitness sharing and mating restrictions. Multiobjective ranking is based on the concept of the dominance of an individual. Whilst an individual may be beaten by another on any given objective, it is ranked 0 when outperformed by no other individual in terms of all the objectives. This system of ranking is non-unique: for example a number of individuals may be ranked 0 and these are said to be non-dominated. Ranking may also be combined with goal and/or priority information to discriminate between non-dominated solutions. For example, a solution in which all the goals are satisfied may be considered superior, or *preferable*, to a non-dominated one in which the goal points of some objectives are not met [11]. All the preferred individuals thus achieve the same fitness, however the number of actual off-spring may differ due to the stochastic nature of the selection mechanism. Thus an accumulation of the imbalances in reproduction can lead the search into an arbitrary area of the trade-off surface. This phenomenon is known as genetic drift and can drastically reduce the quality and efficiency of the search.

Proposed as a solution to genetic drift, fitness sharing penalizes the fitness of individuals in popular neighbourhoods in favour of more remote individuals of similar fitness [11].

Recombining arbitrary pairs of non-dominated individuals can result in the production of an unacceptably high number of unfit off-spring, or lethals. A further refinement to the MOGA is therefore to bias the manner in which individuals are paired for recombination, often termed mating restriction. This restricts reproduction to individuals that are within a given distance of each other. The population diversity is maintained by adding random genetic information at each generation as well as mutating existing individuals.

### IV. THE TESTING PROCEDURE

The testing procedure was undertaken with the underlying aim of producing an unstable time response from the simplified plant model used in this assessment. The Simulink system model used for this exercise was a five loop, decoupled system. Each loop provided a representation of one of the bearing control loops of the AMB rig described in Section II. The plant model was parametrized so that the four transfer functions representing the radial bearings were stable whilst the fifth, representing the axial/thrust bearing, was conditionally stable, exhibiting instability over a small range of gains. The closed-loop structure was unity gain, negative feedback with standard PID controllers for each loop. The Simulink model was parametrized in this way to for two reasons. Firstly, such a model reflects the AMB rig as it is believed to be from empirical data at this time. Secondly, the presence of only a small range of instability within the system poses a difficult test for the MOGA optimization as it attempts to destabilize the system. Should the MOGA prove capable of generating a disturbance event that exposes this small region of instability within the gain range of the axial loop model, this would increase confidence in the MOGA's ability to expose any instability that may be present in the rig.

Three types of signal were used to construct the applied disturbance, a pulse for impulse approximation, a sinusoid and a step. The closed-loop model was configured in order to allow a combination of these signals to be dispersed among the five control loops. The disturbance events were injected between the controller and the plant model in order to represent the effect of injecting disturbances into the power-amps of the rig.

The MOGA was used to select the parameters of the disturbance event. The encoded chromosome of each individual contained information relating to the magnitude of the step signal, the height and duration of the pulse and the frequency and amplitude of the sinusoidal signal. The MOGA was also used to determine the combination of these three signals to be applied to an individual control loop. Also, the disturbance event in each control loop could potentially be comprised of a different combination of signals. This broad-ranging approach to the testing procedure was designed to allow the MOGA the widest possible scope

to explore the model's response to different disturbances. In this way, it was hoped that increased confidence could be placed in the comprehensive nature of the testing procedure; an important feature for future on-line application.

The closed-loop model was configured to apply the disturbance event generated by the MOGA, remove it after a period of 0.2 seconds and then record the system's response. Each candidate disturbance event was then assessed in terms of the MOGA's objectives. The MOGA allows optimization objectives to be expressed in the form specified by the design engineer, rather than being comprised by the need to characterize an objective in a mathematically tractable form. Hence, the objectives were defined as being the reciprocal of the settling time, the reciprocal of the mean absolute error and the reciprocal of the number of bearing impacts resulting from each disturbance weighted to favour those impacts occuring later in the record. As the objective of the testing procedure was to destabilize the system through increasing the settling time, the mean absolute error and the number of bearing impacts, reciprocal values had to be used. The MOGA then optimized towards a destabilizing signal by minimizing the reciprocal values. A further objective was defined to indicate the stability of the rig. This indicated instability in the absence of a detectable settling time following the removal of the disturbance.

## V. RESULTS

Figure 4 shows the parrallel co-ordinates graph resulting from the MOGA-tuning of disturbance signal parameters which were then applied to the simplified AMB model.The sixteen objectives shown in Table 1 are identified along the x-axis. Each line represents the performance in the objective domain of a disturbance event. The crosses which are ranged across the graph denote the goal values for each objective. The y-axis ranges of the graph have been normalized in order to position these crosses at the top of the graph.

Competition between adjacent objectives on the parrallel co-ordinates graph is indicated by crossing lines whereas concurrent lines represent non-competing objectives. It can be seen from the graph that lines between objectives 1 and 2 are concurrent indicating that these objectives are non-competing. This means that a disturbance event that causes a large mean of absolute error for the axial bearing also causes the bearing to exhibit a longer settling time as would be expected. Between objectives 3 and 4 there is a significant amount of line crossings. This indicates that a disturbance event that causes a large number of axial back-up bearing impacts does not cause a large mean of absolute error on the DEX bearing.
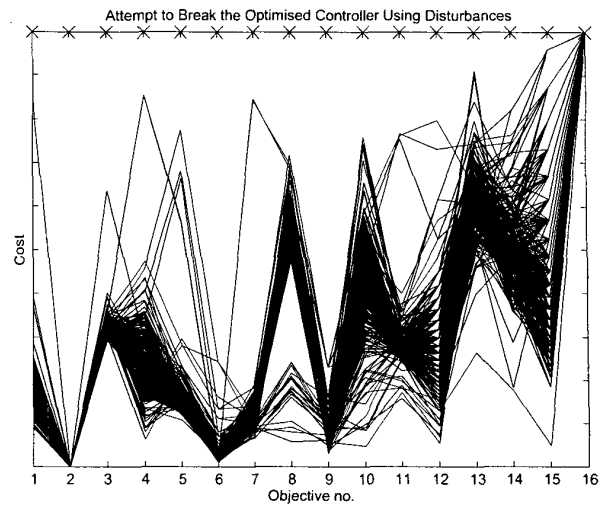


Figure 4. Parrallel co-ordinates graph resulting from disturbance event optimization

| Objective No. | Objective Description |
|---|---|
| 1 | 1/mean(abs(error)) - Axial |
| 2 | 1/settling time - Axial |
| 3 | 1/number of impacts - Axial |
| 4 | 1/mean(abs(error)) - DEX |
| 5 | 1/settling time - DEX |
| 6 | 1/number of impacts - DEX |
| 7 | 1/mean(abs(error)) - DEY |
| 8 | 1/settling time - DEY |
| 9 | 1/number of impacts -DEY |
| 10 | 1/mean(abs(error)) - NDX |
| 11 | 1/settling time - NDX |
| 12 | 1/number of impacts - NDX |
| 13 | 1/mean(abs(error)) - NDY |
| 14 | 1/settling time - NDY |
| 15 | 1/number of impacts - NDY |
| 16 | 1/No. of unstable loops |

Table 1

Key:(See Figure 1)
Axial - The axial or thrust bearing
DEX - Radial bearing on the x-axis at the drive end
DEY - Radial bearing on the y-axis at the drive end
NDX - Radial bearing on the x-axis at the non-drive end
NDY - Radial bearing on the y-axis at the non-drive end

Figures 5 and 6 show the time responses for each bearing resulting from one of the disturbance events chosen from the parrallel co-ordinates graph shown in Figure 4. As can be seen from the responses, the radial loops are, of course, stable. The axial loop can clearly be seen to have gone unstable as a result of the disturbance event produced using the MOGA. The response does not settle and continues to oscillate between its maximum and minimum values (representing the presence of the back-up bearings) after the

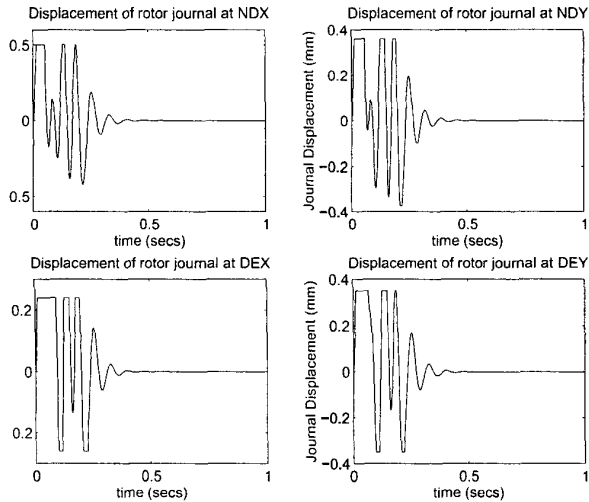disturbance event has been removed.



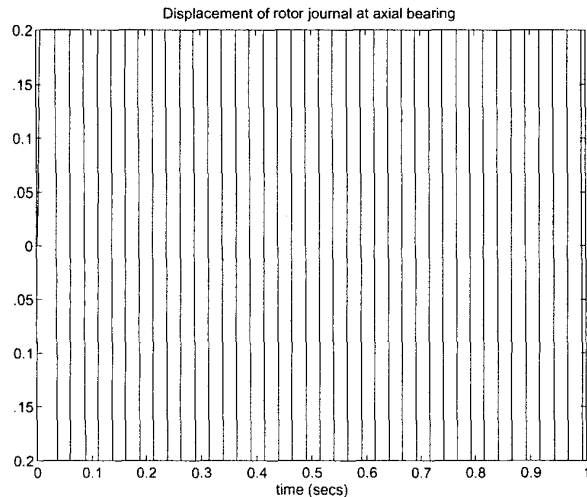Figure 5. Time responses to an optimized disturbance event of the radial bearings



Figure 6. Time responses to an optimized disturbance event of the axial bearing

## VI. CONCLUSIONS

A MOGA has been used to optimize the parameters of a disturbance event. This disturbance was then applied to a simplified model of a 5 bearing AMB system. The objectiv e of the optimization was to cause instability in the model. This simplified model w as parametrized in order to offer only a small gain-range of instability for the MOGA to exploit, thereby posing a difficult search problem.

It can be seen from the time responses that the MOGA was successful in producing a disturbance event which caused instability in the conditionally stable system representing the axial control loop. This clearly demonstrates the ability of the MOGA to produce a disturbance event

which can destabilize a system which is stable for all but a very small range of gains in one loop. It was therefore concluded from this off-line assessment that this particular controller testing and validation technique would be suitable for use on-line. A high degree of confidence could be placed in the technique's ability to uncover any unstable behaviour within a plant which exhibits stable behaviour under the vast majority of circumstances.

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