MBC 500
Magnetic Bearing System
Operating Instructions

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Safety Instructions

Use the following safety guidelines to help protect your magnetic bearing system from potential damage and ensure your own personal safety. The general safety related label is located on the back panel of the unit.

- Do not operate your system with any covers, rotor guards, or cabinet panels removed.
- Levitate the shaft by closing the "loop switches" before rotating manually or using air-turbine drive.
- To help avoid potential damage to your system, be sure the operating voltage at your location is either 115 volts 60 Hertz or 230 volts 50 Hertz.

- To help prevent electric shock, plug the system power cable into a properly grounded electrical outlet. The power cable is equipped with a three-prong plug to help ensure proper grounding. The main ground stud is mounted on the chassis plate inside the unit close to the power inlet and is labeled with "PE".

- Do not use adapter plugs or remove the grounding prong from a cable. If you must use an extension cable, use a three-wire cable with properly grounded plugs.

- Be sure that nothing rests on the power cable and that cables are not located where they can be stepped on or tripped over.

- Do not spill food or liquids on your system.

- Do not push any objects into the openings of your system. Doing so can cause fire or electric shock by shorting out interior components.

- Keep your system away from radiators and heat sources and do not block cooling vents. Avoid placing your system in a closed-in wall unit or on unstable surfaces.

1.0 Introduction and Power Up

The MBC 500 is a magnetic bearing research experiment consisting of two active radial magnetic bearings and a supported rotor mounted on top of an anodized aluminum case. The shaft is actively positioned in the radial directions at the shaft ends (4 degrees of freedom), it is passively centered in the axial direction, and it freely rotates about its axis. Included in the system are four linear current amplifier pairs, one pair for each radial bearing axis, and four internal lead-lag compensators, which independently control the radial bearing axes. If your unit comes with the Turbo 500 option, please see appendix B for more information.

The front panel (figure 1) is a graphical representation of the system dynamics with 12 BNC connections for easy access to system inputs and outputs. Four front panel switches allow the user to open the loop for the internal axis controllers independently. By switching off only a single loop the user can perform simple single-input single-output control design experiments. With all internal loops open a sophisticated 4 by 4 external controller can be implemented. The control bandwidth is roughly 1 kHz so external controllers are typically DSP-based or analog.

MBC 500 research experiments may include single-input single-output identification, multi-input multi-output identification, classical control design, feedback linearization, nonlinear control synthesis, multivariable control synthesis, adaptive control design.

Warnings

The MBC 500 rotor was not designed to be externally driven. Manual spinning of the shaft to demonstrate levitation is encouraged, but rotation above 5,000 RPM poses hazards to persons coming into contact with the spinning shaft as do electric drills etc. Rotation above 15,000 RPM may cause mechanical failure and projectile hazards. Units with the optional air-turbine drive incorporate rotor guards with interlock circuits to prevent contact with the rotor.

Disassembly of the MBC 500 chassis puts persons at risk of electrocution, as voltages up to 240 VAC are present internally. Damage due to disassembly is not covered by the warranty.

Fusing Arrangement

The internal universal power supply operates with 100-240 VAC at frequency of 50-60 Hz. A back panel power module includes a fuse block that is configured for two fuses. Each fuse is a 5 x 20 mm, 1 Amp slow blow fuse. To change fuses, turn off the unit, disconnect the line cord, open the fuse block/cover, using small blade screwdriver or similar tool, and change each fuse as required.

Power Up

Plug in your MBC 500 to a 50-60 Hz power source and turn on the power using the back panel switch. Make sure that the loop switches are closed. The system shaft should be levitated and all the green front panel levitation indicators should be on. Spin the shaft manually and observe the low friction of the magnetic bearings — welcome to the world of active magnetic suspension.

2.0 User Interface

The MBC 500 user interface is via the system front panel shown in figure 1. Four (4) inputs and eight (8) outputs are provided at various points in the system. The input impedances are 33k ohm and the output impedances are 1k ohm. The internal compensator is activated or deactivated with the front panel "loop switches."

Reference or control voltages can be applied at the left most BNC connectors labeled "input." Outputs for identification experiments or external feedback control are provided prior to internal current amplifiers and following the internal gap sensors—these

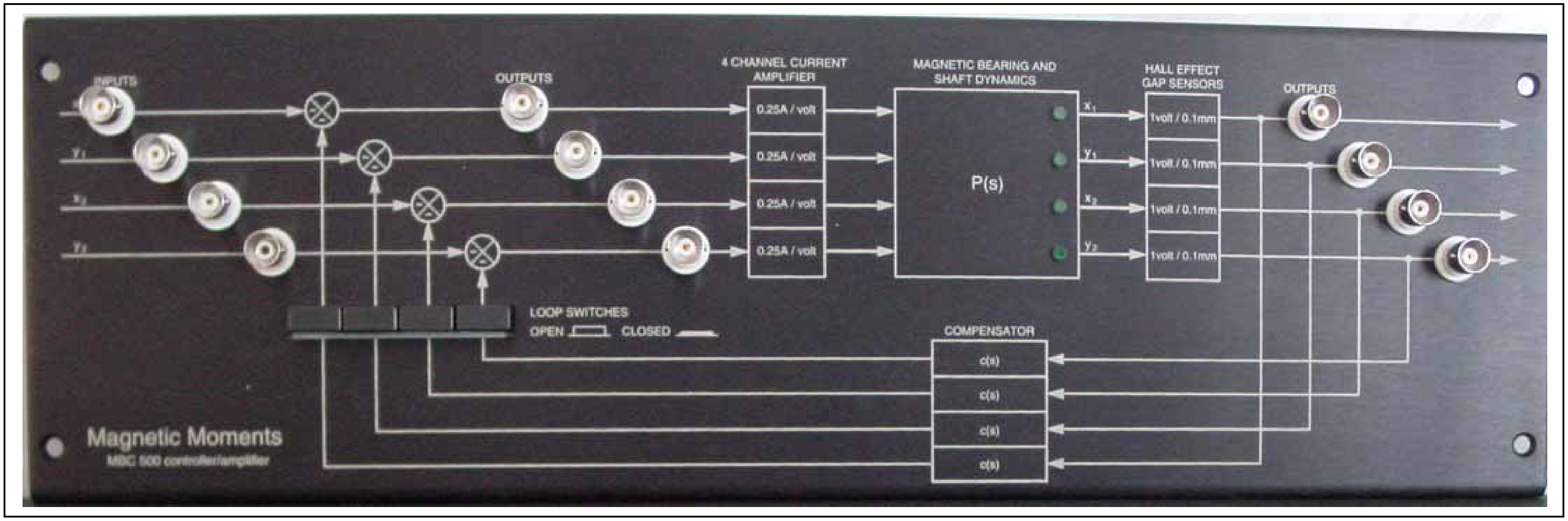

Figure 1 Front Panel block Diagram

are labeled “outputs.” Note that external control voltages can be applied to the input BNC’s whether or not the loop switches are open. The inputs saturate at 6 volts and the sensor output lies in the range ±5 including their voltage offset (< 1 volt).

3.0 System Parameters

This section describes the blocks shown in figure 1 in some detail. The models given are nominal and serve as a guide only. Identification experiments are the best way to establish accurate system models. These can be augmented to include the nonlinearities described here. We begin with a sketch of the magnetic bearing and shaft assembly shown in figure 2.

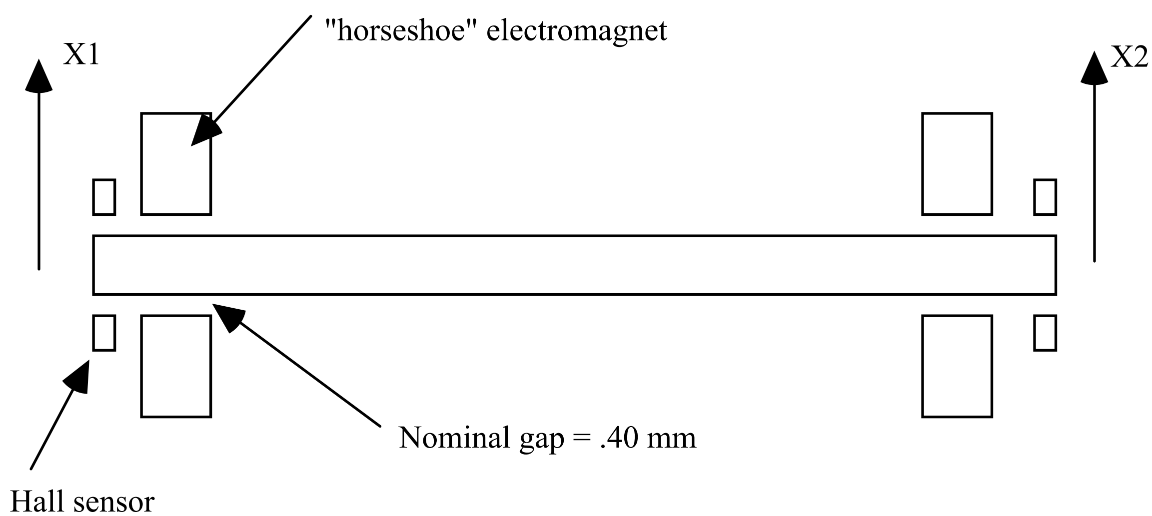

Figure 2 Shaft schematic showing electromagnets and Hall-effect sensors.

Shaft Parameters

The shaft is made from non-magnetic 303 stainless steel with modulus of elasticity 28 x 10^6 psi (1.97 x 10^5 MPa), density 0.29 lb/in^3 (8 x 10^{-3} kg/cm^3), diameter 0.490 inches (1.24 cm), and length 10.6 inches (26.9 cm). The bearings are centered 0.95 inches (2.4 cm) from the shaft ends, and the Hall sensors are centered 0.11 inch (0.28 cm) from the shaft ends.

Bearing Parameters

The bearing coils have a 0.5 Amp bias upon which a control signal is superimposed. The force applied by a single horseshoe electromagnet (see sheet 7 of the circuit schematic) is:

$$F = k(i_{control} + 0.5)^2 / g^2$$

where $k = 2.8 \times 10^{-7}$ Newton - meter^2 / amp^2, $i_{control}$ is the control current supplied by the current amplifier in addition to the 0.5A bias current, and g is the gap in meters. The bias current in opposing electromagnets has opposite sign and when the control current is added to BOTH coils the net force generated by opposing electromagnets is:

$$F_x = k\frac{(i_{control} + 0.5)^2}{(x_1 - .0004)^2} - k\frac{(i_{control} - 0.5)^2}{(x_1 + .0004)^2}$$

where x_1 is the displacement of the shaft inside the left bearing of figure 1. The same expression holds for bearing #2 and the y forces as well.

Amplifier Model

The current amplifier model has a simple first order response. Each of the four current amps is described by:

$$i_{control} = \frac{0.25}{(1 + 2.2 \times 10^{-4} s)}\ A / volt \times V_{control}$$

Compensator Model

The nominal compensator model is derived from the circuit schematic and relates $V_{control}$ to V_{sense} by the following transfer function:

$$V_{control} = \frac{1.45(1 + 0.9 \times 10^{-3} s)}{(1 + 3.3 \times 10^{-4} s)(1 + 2.2 \times 10^{-5} s)} V_{sense}$$

This compensator can be implemented in an external controller, but expect to spend some time tuning. Small magnetic bearings are fast nonlinear unstable multivariable systems...

Sensor Nonlinearity

The displacements sensed by the two opposing Hall Effect sensors shown in figure 2 are combined electronically to yield the following relationship between shaft end displacements X1, X2, Y1, or Y2. Expressed in terms of X1 we have (approximately)

$$V_{sense} = 5\ Volts/mm\ X_1 + 24\ Volts/mm^3\ X_1^3 \pm 1 Volt\ offset$$

V_{sense} is available on the front panel via the sensor output BNC connector.

Schematics

Functional circuit schematics are provided in the appendix.

5.0 Suggestions

As mentioned earlier, small magnetic bearings are fast, nonlinear, unstable, and multivariable systems. They are difficult to control. When testing controllers, instability is common and noisy contact with the brass back-up bushings is common. Don’t be disturbed by this, the mechanical design is rugged. In fact the bearing shaft makes a good handle for carrying the bearing. Continuous operation with the noisy mechanical contact will eventually cause failure of the shaft target laminations, however. Keeping a tight “lag budget” is important in each component of your controller. An easy way to start with the MBC 500 is with identification experiments. These must be performed with the internal controllers activated since the open loop system is unstable. Inject your test signal in the input, use the output prior to the current amplifier as the reference and take the sensor output as the test.

Start your closed loop control experiments by augmenting the internal analog control with your external control. Adding integral control to the internal lead-lag controller is a good first experiment. From there on out there is much unexplored territory in nonlinear control, adaptive control, multivariable control etc.

Warranty

The MBC 500 is guaranteed to be free from manufacturing defects for 120 days from date of shipment. Disassembly , mechanical abuse, and exceeding voltage limits of the system void the warranty.

Appendix A
System Schematics

Supplied with purchase of MBC 500

Appendix B
Turbo 500 Option

The Turbo 500 option provides an internal air turbine drive for the MBC 500 rotor. By using the turbine drive researchers and students can observe the function of the magnetic bearings up to speeds of ±10,000 RPM. Additional experiments such as turbine speed control, and imbalance control can be performed. A considerable amount of hardware is incorporated into the Turbo 500 option and includes 1) bi-directional air turbine and turbine housing mounted on the top plate 2) rotor quadrature optical encoder, 3) Atchley Controls 204PN precision two-stage pneumatic servovalve, and 4) turbine interface electronics which includes a ±10,000 RPM speed limiter, servovalve current driver, rotor guard safety interlock circuitry, and encoder frequency to voltage converter.

THE AIR TO THE TURBO 500 IS AUTOMATICALLY SHUT OFF WHEN THE ROTOR GUARD IS NOT IN PLACE. DO NOT DEFEAT THE INTERLOCK SYSTEM — IT HAS BEEN CAREFULLY DESIGNED FOR YOUR PROTECTION.

The servo valve is a precision component with the following specifications; please contact Moog Industrial Controls at 300 Jamison Rd, East Aurora, NY telephone: 716-655-3000 for more detailed information.

Atchley Controls 204PN Servovalve

Air Supply	Filtered to less than 25 micron, dried so that dew point is less than 20 degrees below ambient temperature.
Design	Two Stage
Flow into First Stage	0.17 SCFM (0.0048 m^3/min.) at 100 psi (689.5 kPa) supply (turbo 500 is internally regulated to 60 psi, 413.7 kPa)
No Load Cylinder Flow	4.5 SCFM (0.127 m^3/min.) at 100 psi (689.5 kPa) supply. (Turbo 500 orifice load limits flow to about 1 SCFM = 0.028 m^3/min.)
Hysteresis	3% max of rated current
Threshold (spool friction)	0.02% max of rated current
3 db bandwidth	30Hz
Coil	±20ma (5V into 250 ohms)

The rear panel connections provide the turbine option I/O interface as follows

Ch A	TTL level output from rotor optical encoder (2 counts/rev).
Ch B	Same as A and shifted roughly 90 electrical degrees.
Control	±5V servovalve coil current command (4ma/volt).
Speed	Bipolar speed signal with sensitivity of 0.1 Volts per 1000RPM. This signal is derived from the optical encoder output and is not reliable at low speeds.