DESIGN CONSIDERATIONS FOR AN ACTIVE MAGNETIC BEARING USED IN AEROSPACE ENVIRONMENTAL CONTROL SYSTEMS

Mark Fairbert
Barber-Colman Aerospace, Loves Park, Illinois, USA, mfairbert@siebe-ec.com

ABSTRACT
The purpose of this paper is to share with magnetic bearing enthusiasts the design considerations that have lead to the successful application of an active magnetic bearing system used in aircraft environmental control system. The use of a magnetic bearing system in an aerospace application must meet the rigid standards for in-flight systems. This includes both mechanical and electrical operational and safety requirements. An introduction to the application of the magnetic bearing will be explained. A detailed discussion of the C-130E magnetic bearing system will explain the physical design of the bearing assembly and the design of the control system. Further discussion will explain the significance of the manufacturing process and minimizing the costs of maintainability of the magnetic bearing system in the field. Milestones of the magnetic bearing development and operational data will be provided.

INTRODUCTION
The task of the environmental control system is to convert high temperature, jet-engine bleed air, into cool air for aircraft temperature control and pressurization. The component responsible for this temperature conversion is the Air Cycle Machine. Traditionally, ball bearing or air bearing technology has supported the shaft of an air cycle machine. Poor reliability and high maintenance costs have lead to the development of the Magnetic Bearing Air Cycle Machine (MBACM). FIGURE 1 shows a simplistic diagram of a typical aircraft environmental control system with a MBACM. The MBACM in this design is configured as a bootstrap turbo-compressor machine.

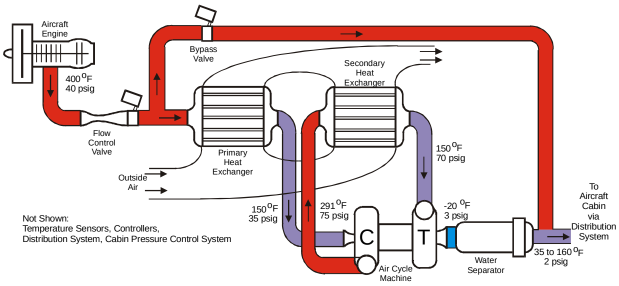

FIGURE 1: Aircraft Environmental Control System

Bleed air from the aircraft propulsion engine is routed through a primary heat exchanger to drop the compressor inlet air temperature to approximately 66°C, the compressor inlet is the input to the MBACM. The mass flow rate of the incoming air at normal operating conditions is 31.75 kg/min. The air is then compressed, raising the air temperature to approximately 144°C and passed through a secondary heat exchanger. The secondary heat exchanger will drop the air temperature to approximately 66°C. Secondary heat exchanger air is then delivered to the turbine inlet. The turbine inlet drives the MBACM shaft, aiding in the compression of the incoming air. The work required turning the shaft removes energy from the air, providing a dramatic decrease in air temperature. Typically, the turbine outlet air temperature will reach -20°C; the turbine outlet is the output of the MBACM. The turbine outlet air is then mixed with warm air through a temperature-controlled valve and distributed throughout the aircraft.

C-130E APPLICATION

FIGURE 2 shows a photograph of a C-130E magnetic bearing assembly. The shaft is shown with the compressor (left side) and turbine wheels. The radial laminations can be seen to the right and left of the thrust disk. The bearing housing is configured as a proprietary "clam-shell" design. This design splits the housing into two separate pieces and allows for ease of manufacturing and assembly. Not shown are the compressor and turbine scrolls that connect the bearing assembly to the bleed air system. The housing is constructed of aluminum and designed to contain all debris in the event of a thrust disk rupture. Containment is required for high-energy rotating equipment in aerospace applications.

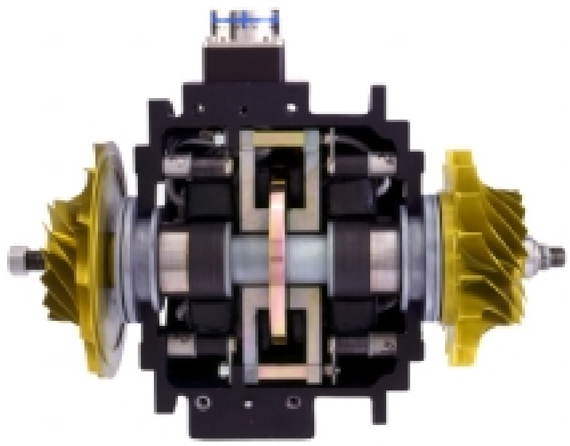

FIGURE 2: C-130E Magnetic Bearing

C-130E Magnetic Bearing Characteristics

Physical Characteristic

Total bearing mass	12.0 kg (26.5 lbs)
Controller mass	5.0 kg (11.0 lbs)
Shaft mass (with C/T wheels)	1.5 kg (3.3 lbs)
Shaft length	24.1 cm (9.5 in)
Shaft diameter (laminations)	3.3 cm (1.3 in)
Maximum radial force	98 N (22 lbs)
Maximum thrust force	756 N (170 lbs)
Shaft operational speed	66,000 RPM

Electrical Characteristics

Controller operating voltage	28 VDC
Controller operating current	3.5 amps*
Radial and Thrust coil current	0 to 20 amps
Maximum power consumption	100 Watts*

*Nominal

C-130E MAGNETIC BEARING DESIGN

Extensive simulation and testing is used in designing the shaft system. Stress and thermal analysis is completed on all shaft sub-assemblies. These sub-assemblies include tie-bolt, laminations, thrust disk, compressor wheel and turbine wheel. The final shaft assembly includes stress and thermal analysis and rotor-dynamics analysis. The rotor-dynamics analysis is an important consideration for position control compensation. Results of the shaft rotor-dynamics analysis are shown in FIGURE 3.

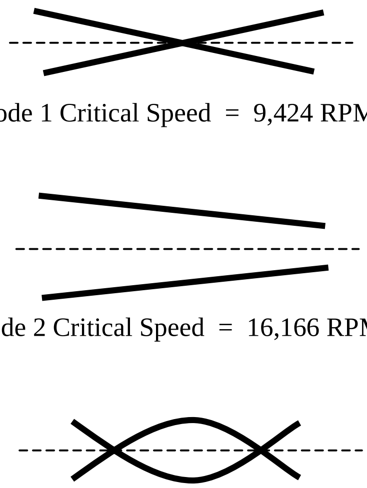

FIGURE 3: C-130E Shaft Rotor-Dynamics

The magnetic bearing is designed to operate between the mode 2 and mode 3 critical speeds. The mode 3 critical speed represents the natural frequency of the shaft assembly and is the first bending mode of the shaft. The control system at the Mode 3 frequency would have zero damping allowing the shaft position control to remain unstable.

If the MBACM is operated outside of the design specification a backup bearing contains the shaft assembly within a physical barrier of the MBACM housing. This protects the electromagnetic pole faces from contact. Contacting the pole faces would change the electromagnetic characteristics of the magnetic bearing. In the event of severe out-of-tolerance operation the backup bearing will minimize permanent damage to the MBACM.

The temperature gradient on the MBACM assembly during operation, from compressor outlet to turbine outlet, can be as high as 200°C. This temperature gradient is responsible for a 25% reduction in total shaft travel in the thrust axis due to housing thermal growth. This circumstance is nullified by electronically offsetting the shaft thrust reference proportional to the

direction of the thermal growth. This requires the shaft position control compensation to be robust enough to provide stable control of the shaft while the inductive air gap is changing. Once the bearing temperature has stabilized the thrust air gap will remain constant.
The magnetic bearing system uses a total of five position sensors for position feedback to the controller. Four position sensors are used for the x and y axis on each end of the shaft. The fifth position sensor is used for the thrust (axial) position sensing. Radial sensors are mounted within the bearing assembly and are orientated in the same axis as the electromagnets. The thrust sensor is contained within the thrust sensor housing located on the compressor inlet scroll. The sensors are a proprietary design and produce a voltage linearly proportional to shaft travel. All sensors are temperature compensated to maintain linearity to ± 2% of the total sensing distance.

C-130E MAGNETIC BEARING CONTROLLER

The magnetic bearing controller is designed to meet all requirements for airborne electronic applications. These requirements include EMI, environmental stresses and input power transients. Extensive testing and documentation are required for system qualification. FIGURE 4 shows a block diagram of the controller.

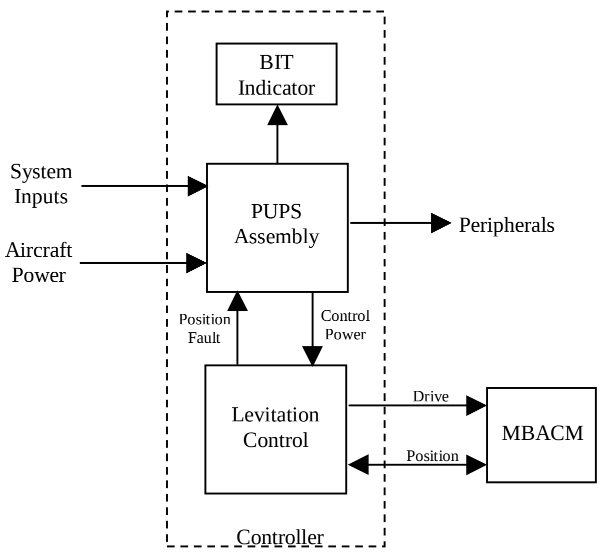

FIGURE 4: Controller Block Diagram

The controller is powered by 28 VDC. There are two independent sources of power in the event of a primary power source failure. Power switching to the secondary source has no effect on the control system while the shaft is levitating. Power is monitored and controlled by the Power-up Sequence (PUPS) assembly. The PUPS assembly is the interface between the controller and the other environmental control system (ECS) components. The PUPS assembly is controlled using a programmable logic device. ECS inputs can include temperature sensors, current sensors, weight-on wheels, etc. All inputs are converted to 5 volt logic levels. There are two primary outputs from the PUPS assembly. One primary output is the ECS flow control valve open/close. In the event of a system malfunction the flow control valve is closed, limiting the risk of secondary failures. The second primary output is to the levitation control circuits.
While the system is normally operating, the MBACM shaft is levitated prior to the flow control valve being opened. When the ECS system is secured the shaft is allowed to “spin-down” before levitation is disabled. The PUPS assembly also monitors the output of the position error detection circuit. When the shaft is out of its specified operating parameters a BIT indicator will be enabled. A position fault detected indicates a bearing malfunction, intermittent or transient faults are rejected.
Levitation control is comprised of three sub-systems, the position sensing system, feedback compensation and the coil drive system.

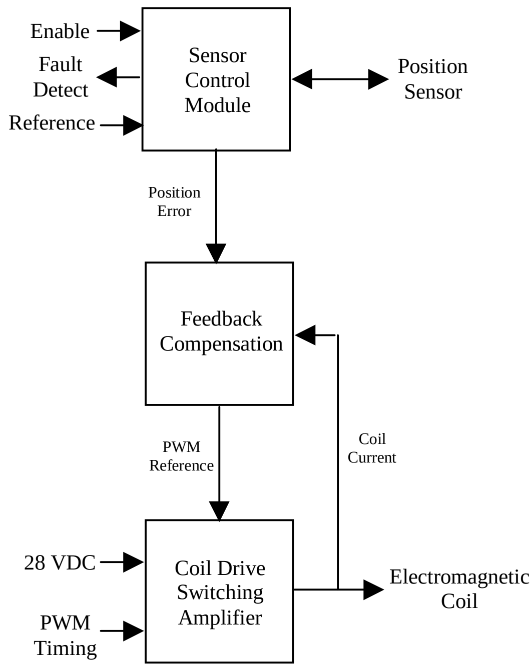

FIGURE 5: Shaft Levitation Control

Each position sensor interfaces with its own control module. The control module is responsible for generating the excitation signal for the eddy-current sensors and detecting the position displacement of the shaft. A position reference signal is used to determine the center position error signal. The sensor modules also contain the temperature compensation circuits to maintain linearity. The output signal of the sensor control module is applied to the feedback compensation circuit.

The controller uses separate control compensation networks for radial and thrust control. Simulation and data collection are used to determine and verify correct control system response. FIGURE 5 and FIGURE 6 show the block diagrams of the radial and thrust compensation circuits respectively.

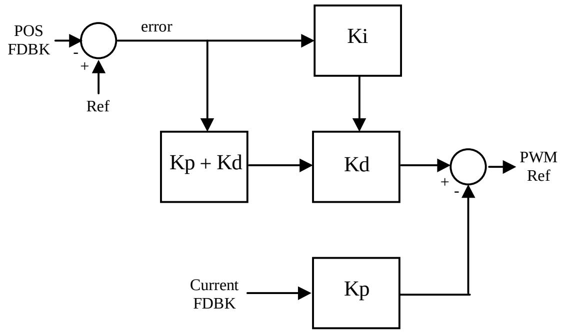

FIGURE 5: Radial Feedback Compensation

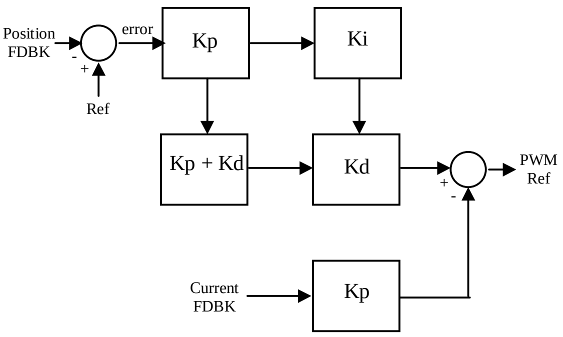

FIGURE 6: Thrust Feedback Compensation

All radial channels have identical compensation characteristics. Compensation characteristics are gain, phase, bandwidth and step response. Consideration is given to the Mode1 and Mode 2 critical speeds; these represent resonances to the radial compensation network. Thrust compensation characteristics are independent of radial characteristics. Additional gain is required for thrust control to compensate for the transient disturbance forces associated with the input bleed air in the axial direction. Coil current feedback for radial and thrust bearing control is also provided for increased stability. The output of the compensation network is applied to the coil drive circuit.

Vibration of the aircraft is also considered for the thrust and radial control compensation. Sufficient bandwidth is present to compensate for the vibration disturbance force. FIGURE 7 shows the vibration profile for the C-130E application.

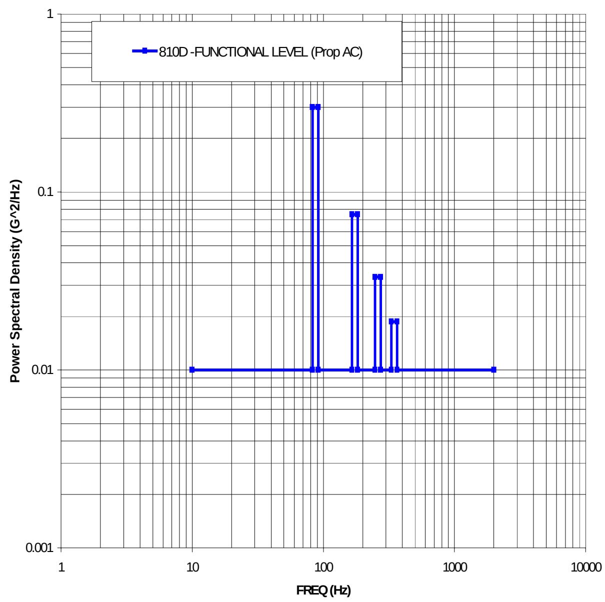

FIGURE 7: Vibration Power Spectral Density vs. Frequency

The coil drive circuit is configured as a DC switching amplifier. FIGURE 8 shows the switching amplifier configuration.

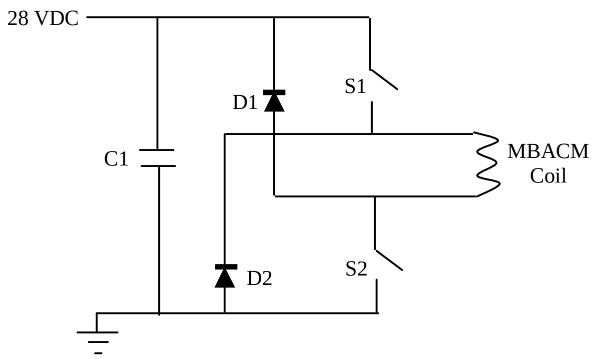

FIGURE 8: Coil Drive Switching Amplifier

This configuration allows for the most efficient use of the 28 VDC supply. S1 and S2 are closed simultaneously allowing current to build in the electromagnetic coil. C1 provides a low impedance source for the coil current. When S1 and S2 are opened current flows through the return diodes and recharges C1. The 28 VDC supply will charge C1 to full capacity due to system losses. S1 and S2 are low R_{ds}(on) MOSFET devices. Low R_{ds}(on) minimizes the power losses of the switching devices.

MAGNETIC BEARING MANUFACTURING

Magnetic bearing manufacturing is critical to the success of a magnetic bearing program intended for quantity production. The air gaps completing the inductive circuits between the shaft and the electromagnetic pole faces leave no room for poor quality of manufactured parts or undisciplined manufacturing processes. The "clam-shell" design and an innovative manufacturing process have enabled the air gap tolerance to be within ± 5% of the total shaft travel. This consistency allows the margins of the control system to account for manufacturing tolerances and provide stable control. Also, there is no need to re-tune the controller for each magnetic bearing assembly.

FIELD REPLACEMENT

Current development includes a method where untrained personnel can easily interchange the magnetic bearing controller and the bearing assembly in the field. This is accomplished through the use of an automatic calibration system. This system automatically determines the shaft reference signal used by the position control compensation network. In the event of a controller failure, the bearing assembly would not need to be replaced. The new controller is then calibrated with the bearing assembly automatically. Also, predetermined shaft position offsets can be automatically programmed to improve shaft position control.

FIGURE 9: KC-135 MBACM and Controller

MBACM DEVELOPMENT MILESTONES

February 1993 – MBACM 3 attains an operating speed of 104,000 RPM.

January 1996 – KC-135 MBACM is the first flight-tested magnetic bearing application.

July 1996 – MBACM 3 completes 18,332 hours of continuous operation at 70,000 RPM.

April 1998 – KC-135 MBACM accumulates 2,000 hours of flight-test time. Total operational time is 4,000 hours.

May 2000 – C-130E MBACM accumulates over 1000 hours of rotational testing and over 1,500 hours of total levitation testing. Testing simulates all aircraft operating modes.

3rd Quarter, 2000 – Flight-testing the C-130E MBACM begins.

C-130E TEST DATA

Operational test results are shown in FIGURE 10 through FIGURE 15 in inches. Total record period is 100 msec. TABLE 1 is a summary of the test results. For the rotational test, the mass flow rate applied to the compressor inlet was 31.75 Kg/min (70 lbs/min).

TABLE: 1 Maximum Shaft Displacement from Center Position (mm)

AXIS	0 RPM	66,000 RPM
Compressor x	+0.010/-0.020	+0.051/-0.063
Compressor y	+0.001/-0.011	+0.063/-0.079
Turbine x	+0.015/-0.028	+0.071/-0.028
Turbine y	+0.001/-0.013	+0.041/-0.041
Thrust	+0.015/0.021	+0.016/0.021

CONCLUSIONS

The design of the MBACM demonstrates that an active magnetic bearing is a viable solution to the maintenance and reliability issues with current cooling turbine configurations. The MBACM offers a maintenance free cooling turbine design. The reliability of electronic components surpasses that of lubrication systems currently in use with ball bearing machines. Safety risks are minimized with the virtually friction free operation of the magnetic bearing system.

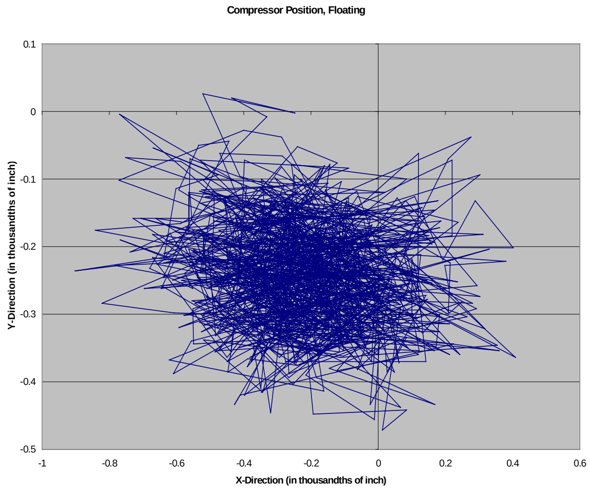

FIGURE 10: Compressor Shaft Position, 0 RPM

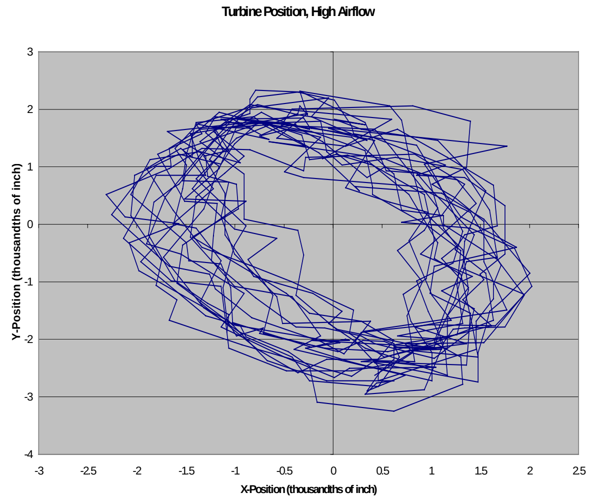

FIGURE 13: Compressor Shaft Position, 66K RPM

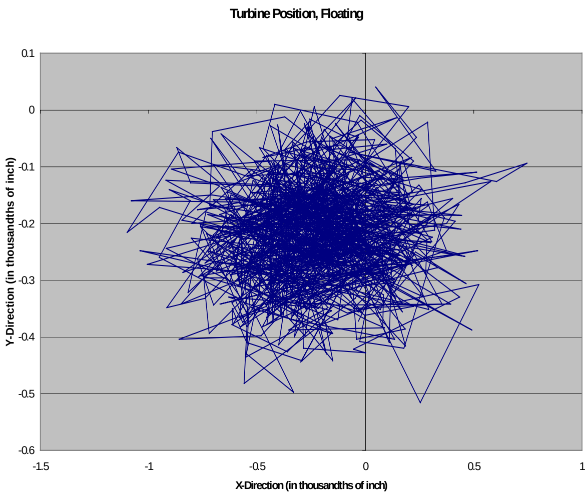

FIGURE 11: Turbine Shaft Position, 0 RPM

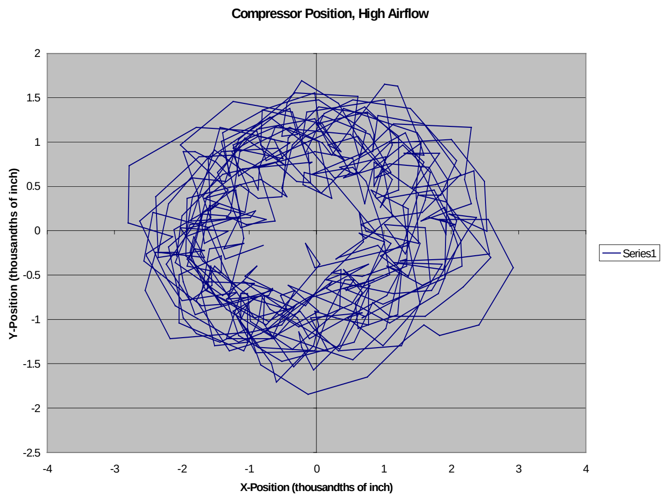

FIGURE 14: Turbine Shaft Position, 66K RPM

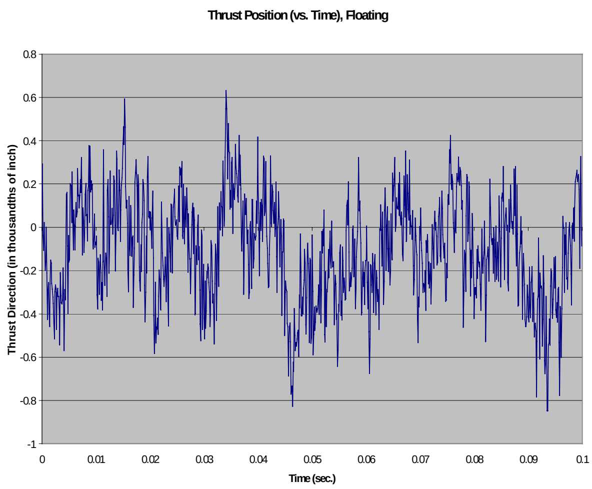

FIGURE 12: Thrust Shaft Position, 0 RPM

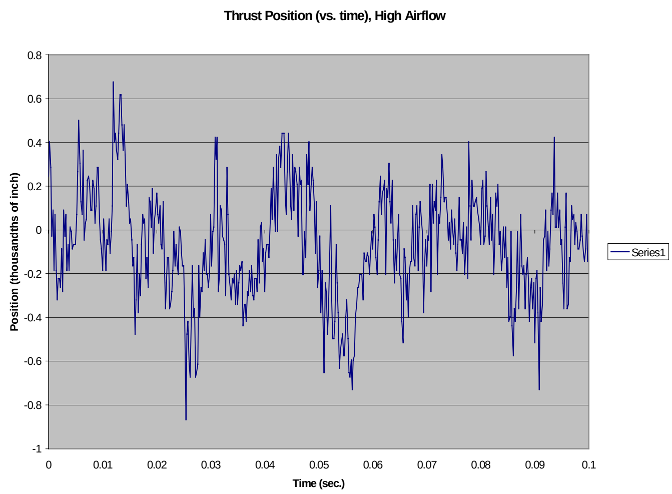

FIGURE 15: Thrust Shaft Position, 66K RPM