Real Time Digital Control of Magnetic Bearings with Microprocessors

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Abstract

This paper presents the work on the real time implementation of digital controllers applied to magnetic bearings to levitate high speed rotor systems. Microprocessor is employed for digital signal processing. The control loop consists of PID controller, tracking and fixed notch filters, lead compensators, and feedforward stage, etc. The controller is implemented with TI TMS320C67 processor incorporated with LabVIEW data acquisition and graphical user interface. Digital signal processing techniques including bilinear transformation, frequency pre-warping, digital filter design and I/O communications are applied to implement the control rule. The real time controller has been successfully applied to the levitations of a Revolver Test Rig in Vibration Control Lab at Texas A&M and the Energy Storage Flywheel System used by industries for vehicles.

1. Introduction

Magnetic bearings are electromechanical suspension systems that imply actively controlled forces applying to the high speed rotor. Closed loop feedback control is utilized to suspend the rotor in a stable fashion, to suppress vibrations and to reject the disturbance such as sensor runout. The control system allows the current in the bearing coil to be controlled by feedback signal from the shaft position. Normally, the control system contains path filters, compensators, amplifiers, actuators and notch filters [1]. The goal of the magnetic bearing controller design is to incorporate the controller into a hardware system for real time implementation. The most popular solution to this problem is to instrument the control system with digital signal processing using microprocessors. With the microprocessor revolution which places a central processing unit on a single integrated chip, the digital implementation of controller has found wide applications in various areas in engineering. Our DSP implementation of the control systems is based on the TI 32-bit processor. In the development of the control system we choose the single-board solution, which integrates the data acquisition, signal processing, memory module and I/O on a stand-alone board.

The tasks placed on the DSP are to implement the control rules to provide means to adjust the forces to support the rotor and stabilize the system. There are total four radial and one axial axes of control channels. Digital computations are made in a number of control stages with intent to provide force control signals. In the mean time an external analog signal can be fed to the control channels as feedforward stage. These signals are digitally processed and then converted to analog form in D/A modules and finally routed to the power servo amplifiers.

2. Single board DSP system and software

The software package consists two main parts: (a) DSP executable code *COFF* file; (b) LabVIEW user interface and auxiliary DSP routines. The hardware consists: (a) SBC67 stand-alone board with Texas Instruments TMS320C67 32-bit microprocessor; (b) two A/D – D/A modules (each has 4 channels). (c) Data acquisition board PCI6071 of National Instruments; (d) SCB100 connector block of National Instruments.

2.1. DSP system hardware and software

The SBC67 single board system is a high performance stand-alone DSP system. It is a 160mm×100 mm card operating independently from host PC and can be freely embedded into custom target systems to perform real time control functions. The single board computer (Figure 1) has dual plug-in sites for interchangeable, modular I/O. The processor core is capable of sustained computational throughput of 1600 MIPS (million instructions per second) fixed point and 1 GFLOPS (gig floating point operations) floating point with parallel processing techniques. The microprocessor operates at 150 MHz. On-chip resources include 64k byte program memory and 64k

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byte data memory. On-chip peripherals include 32 bit counter/timer, an RS232 serial channel and a polarized interrupt controller.

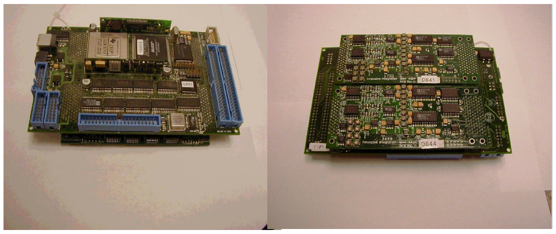

Figure 1. SBC67 board (front and back view)

Data acquisition and I/O module were performed via A4D4 OMNIBUS module. SBC67 board can accommodate two OMNIBUS boards for A/D and D/A conversion. Four chips are incorporated on the A4D4 board for the A/D conversion. The resolution for the AD and DA are all 16 bits. With the SBC67 board incorporated with two A4D4 module boards, the DSP system can process eight channels with a single board.

The development tool is ZUMA Toolset. The ZUMA DSP code development employs the Codewright tool as development environment. The Codewright emulates the window editor so that the user can edit, compile, link and finally build the executable code in COFF (Common Output File Format) file.

2.2. LabVIEW for DSP and GUI

The front panel of the LabVIEW main program is the entrance to access the controller program. The fundamental functions of the LabVIEW controller are to:

a) input or change controller parameters such as PID gains, lead/lag pole locations, DC target voltages, notch filters, DC offsets, cutoff frequencies, etc.;

b) obtain tachometer signal for measuring the shaft speed;

c) perform computations of relevant controller stages as aid to the real time digital signal processing.

As seen from the specifications of the chosen DSP system, the operating speed is as high as 1 GFOLPS. However, the limited 64k on-chip memory of TMS6701 restricts the use of sophisticated control algorithms to be accommodated into the microprocessor. We used LabVIEW packages to undertake part of the computation jobs which are mainly the computations of the digital filter coefficients. There are two main advantages of introducing LabVIEW software in digital signal processing. First, with the aid of a LabVIEW program, coefficient calculations of digital filters can be made in LabVIEW formula frame so that the principal real time filtering process can be resided in the SBC67 DSP on-chip memory. Second, a friendly graphical user interface (GUI) can be built on LabVIEW environment. A handshaking procedure was built between the DSP board system and the LabVIEW package for data communications.

3. Digital signal processing

In the digital signal processing of magnetic suspension controller (MSC), the most common examples are the filters. A robust method that requires moderate amount of algebra is the bilinear transformation:

$$s \approx \frac{2(z-1)}{T(z+1)} \qquad (1)$$

where T is the sampling period. In the decentralized DSP controller the sampling rate is 15000 Hz .i.e. T=1/15000 sec. This formula is substituted for s to convert functions to z domain. The filters used in the magnetic suspension controller are derived below:

Proportional control: 1st order filter with unit gain

$$P_s(s) = \frac{1}{\tau s + 1} \qquad (2)$$

Substituting for s followed by algebraic manipulation gives

$$P(z) = \frac{\frac{T}{T+2\tau} + \frac{T}{T+2\tau} z^{-1}}{1 + \frac{T-2\tau}{T+2\tau} z^{-1}} \qquad (3)$$

Derivative control: 2nd order filter with unit gain

$$D_s(s) = \frac{s}{(\tau s+1)^2} = \frac{s}{\tau^2 s^2 + 2\tau s + 1} \qquad (4)$$

Substituting for s followed by algebraic manipulation gives

$$D(z) = \frac{b_0 + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \qquad (5)$$

The integral controller can be expressed as a 1st order filter and the resulting difference equation is similar to that of the proportional controller.

Lead compensator:

$$L_s(s) = K_{ld} \frac{s - z_0}{s - p_0} \qquad (6)$$

Substituting for s followed by algebraic manipulation gives

$$L(z) = \frac{\frac{2/T - z_0}{2/T - p_0} + \frac{-2/T - z_0}{2/T - p_0} z^{-1}}{1 + \frac{-2/T - p_0}{2/T - p_0} z^{-1}} \qquad (7)$$

It should be noted that the digital filters derived above are not exactly equivalent to analog filters. The bilinear transformation can use prewarping to make the steady state response of the two filters to be the same at certain appointed frequency. This is of special importance to notch filters because we usually require the notch filters to accurately notch off signal at a certain appointed frequency. To apply prewarping, use Equation (8) in place of Equation (1) as an approximation to s:

$$s \approx \frac{\omega_0}{\tan(\omega_0 T/2)} \frac{(z-1)}{(z+1)} \qquad (8)$$

where ω_0 is the frequency at which exact steady state equivalence is desired. The bilinear transformation with prewarping is used for the notch filters in the controller.

Consider the non-symmetric notch filter:

$$\frac{y(s)}{x(s)} = \frac{\varepsilon^2 s^2 + \varepsilon^2 \omega_0^2}{s^2 + \varepsilon \frac{\omega_0}{Q} s + \varepsilon^2 \omega_0^2} \qquad (9)$$

where ω_0 is the notch center frequency, $\varepsilon = 1$ corresponds to the symmetric notch filter. Applying bilinear transformation with prewarping, we have the digital notch filter as

$$\frac{y(z)}{x(z)} = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \qquad (10)$$

4. Control system

The magnetic suspension controller provides a means to adjust the magnetic bearing forces to reduce the positioning errors for the spinning rotor. Position sensor output signals for the 4 radial and 1 axial axes of control are routed to the inputs of the MSC, wherein digital computations are made in a number of control stages with intent to provide force control signals that minimize position errors. These signals are converted to an analog form in D/A modules and then routed to the power servo amplifiers. The target DSP controller and monitor for the flywheel magnetic suspension are incorporated with the LabVIEW programs and the National Instrument data acquisition board. The application programs are installed in the appropriate directory of the host PC. The NI-DAQ board configuration and the input-output signal connections are completed via a 19” rack mountable enclosure. The input analog signals to the DAQ board are connected through SCB-100 Connector Block which is mounted in the enclosure.

The communications between LabVIEW and DSP code are in terms of handshaking. At nominal operating speed of 15000 rpm (250 Hz), the notches can track as high as 15X (the 15th harmonics of the basic sine wave), i.e. 3750 Hz. Figure 2 illustrates the various control stages along any of the 5 control axes in the DSP system. These stages are summarized as follows:

(1) The position sensor’s output signal enters the control path at the upper left of the diagram.
(2) A synchronized sinusoidal feedforward signal is summed with the sensor signal to reduce the effects of runout. The amplitude and phase angle can be adjusted by user.
(3) A DC voltage target signal is then summed to provide the reference voltage for positioning the shaft along this control axis.
(4) The error signal is then routed to the parallel PID paths.
(5) The outputs of PID paths are summed, and the sum is routed to cascaded notch filters. The notches may track the harmonics of the rotor spin frequency or have fixed center frequencies.
(6) The output of the final notch stage is then subject to cascaded lead/lag filters.
(7) The output from the lead stages receives an output gain, typically employed to compensate for non-uniformity in the downstream component (power amplifiers, actuators) gains.
(8) The final output voltage is limited so as not to exceed the 10 volt D/A limit on the I/O hardware module.

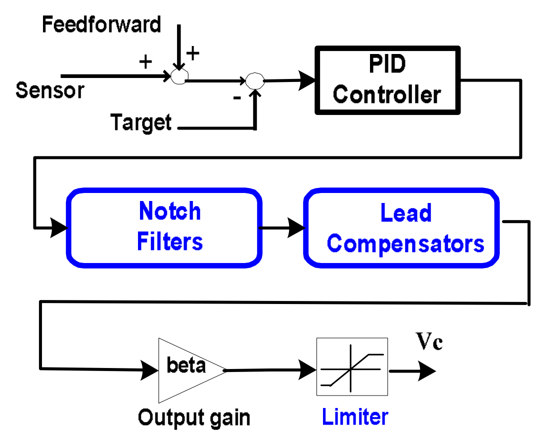

Figure 2. Controller architecture

5. Graphical user interface

The DSP controller settings are made via a LabVIEW Graphical User Interface (GUI). The LabVIEW GUI serves as a virtual instrument that allows the user to enter the control parameters on the front panel of the virtual instrument. Figure 3 is part of the front panel schematic diagram of the controller.

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The graphical user interface makes it easy to enter and update controller parameters. Two main modes of downloading the control parameters from the GUI to the DSP controller are available to the user. These modes are a “Continuous Download” that sends the parameter values to the DSP in real time as they are being changed, or in “Update Download” mode, wherein first, all parameter changes are made, and only then are they sent to the DSP by user clicking the “ Update Download” button. This is particular important for changing the lead compensator parameters: when the pole of the lead is changed, we do not want the controller to update before the zero is entered in order to avoid the controller from malfunctioning.

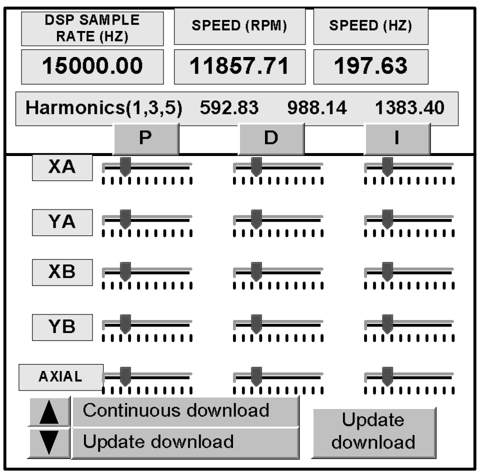

Figure 3. Schematic LabVIEW GUI

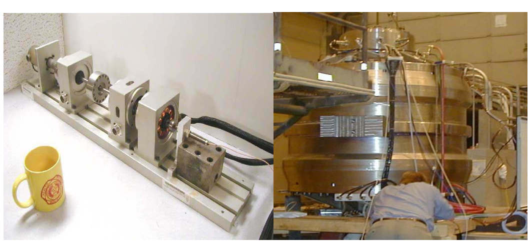

Figure 4. MSC applied to small and big flywheels

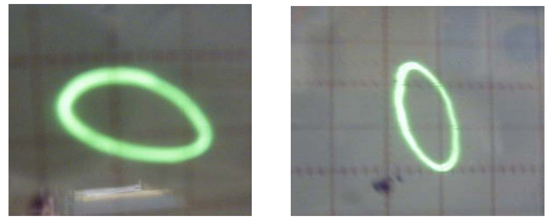

Figure 5. Orbits of magnetic bearing of test rig

6. Conclusions

This approach implements the DSP based real time controller for magnetic suspension of high speed flywheel. The digital controller is realized with TI TMS320C67 processor incorporated with LabVIEW data acquisition and GUI. Digital signal processing techniques including bilinear transformation, frequency prewarping, digital filter and I/O communications are utilized in the controller program. This approach creatively combined the single board computer and the LabVIEW package for real time digital signal processing with friendly user interface. The DSP based real time controller has successfully been applied to levitate the Revolver Test Rig in Vibration Control Lab at Texas A&M University and the Energy Storage Flywheel at UT Austin (see Figures 4 and 5) by suitably adjusting the control parameters to meet individual control need.

7. References

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