Research on Active Vibration Control of Thin-Walled Workpiece in Milling Based on Voice Coil Motor

Puwei Chen, Jie Zhai, Xiaoming Zhang, Hai-Tao Zhang, and Han Ding

State Key Laboratory of Digital Manufacturing Equipment and Technology,
Huazhong University of Science and Technology, Wuhan 430074, China

Abstract. Thin-walled workpieces are widely used in the industries of aerospace, national defense, petrochemistry and so on. Workpiece machining vibration induced by cutting tools greatly affects the milling efficiency and accuracy, and hence vibration alleviation has now become a bottleneck technique for the milling process of thin-walled workpieces. An active control method is developed here to attenuate the milling vibration by using voice coil motors and laser displacement detectors as actuators and sensors, respectively. The control algorithm is embedded in a FPGA module, and the closed-loop system is fulfilled by a FPGA card. Finally, this closed-loop control system is examined by vibration control experiments on a thin-walled aluminium alloy workpiece, where the vibration amplitudes have been decreased by 75% with cutting frequency bandwidth of 15Hz. The feasibility and superiority of the proposed active control method and the closed-loop system are thus verified.

Keywords: Active control, Vibration control, Thin-walled workpiece, FPGA.

1 Introduction

The thin-walled workpieces have been widely used in many industrials because of their excellent properties such as light weight and high strength. Vibration is an inextricable part of machining process which has detrimental effects on part quality,tool life,and productivity. In extreme situations, it may lead to chatter and destabilize the cutting system. The thin-walled workpiece is getting thinner and thinner during cutting process which leads to lower stiffness of the wall,so the cutting force can easily cause the forced vibration of the wall, which will cause bad effects such as deformation of the wall and chatter marks.

So far, there are two mainstream kinds of methods to tackle the control problems of attenuating unexpected vibrations, i.e., passive and active control approaches. The passive control method consists of mounting passive material on the structure in order to change its dynamic characteristics such as stiffness and damping coefficient. However, the passive control method usually leads to an increased weight of structure, which limits its further applications [1]. In special, this method is efficient at high frequencies but tend to be expensive and bulky

J. Lee et al. (Eds.): ICIRA 2013, Part II, LNAI 8103, pp. 503–512, 2013.

at low frequencies [1,2,3], and the effectiveness will be drastically reduced by operation frequency changes of the machining system[4]. Although some recent type of passive controller using piezoelectric connecting to resonant passive electric circuits [5] is light enough, it cannot be used for a sufficiently broad range of frequency control due to its internal dynamics limitations.

By contrast, a more prospective kind of control method is active vibration control (AVC), which uses intelligent actuators (like electro-strictive executors) to generate forces that absorb the energy caused by the unexpected vibrations in order to cancel or reduce their effect on the overall system [3]. The sensors and intelligent actuators form a closed-loop to facilitate controller design. By properly altering system dynamics, an active controller is able to further improve the stability of thin-walled piece machining systems and hence achieves a higher machining efficiency. These years have witnessed the increasing investigations on AVC for flexible thin-walled pieces [6,7]. As representative works, Zhang *et al.*[6] have used an active damping method to attenuate vibrations. Nagaya *et al.* [7] presented a method to drive the tool or workpiece move along the opposite direction of the cutting vibrations, which directly attenuates the vibrations especially in low frequency region. Jenifene *et al.* [1] proposed an AVC method for lightly damped dynamic systems, where a delayed position feedback signal was used to form a closed-loop controller. Kar *et al.* [8] and Xianmin *et al.* [9] applied H_∞ robust control approaches for flexible plate structures, which effectively suppress the low-frequency vibrations caused by external disturbances. Tokhi *et al.* [3] proposed active adaptive control approaches for a flexible beam and a square thin plate, respectively. In both methods, some feedforward control structures are included to enable a pre-cancelation of vibrations at operational points. Tavakolpour *et al.* [2] proposed an finite difference (FD) model based AVC approach, where an effective vibration suppression capability is achieved using piezoelectric actuator with the incorporated self-learning feedback controller. But most of the above-mentioned advanced control methods have not been applied into real machining processes yet but examined by numerical simulations. This paper proposes another active vibration control method. It compensates the milling vibration of thin-walled workpieces by using voice coil motors as actuators in a closed-loop control system. The experimental results show that the closed-loop control hardware platform works well and voice coil motors can efficiently control the vibration of thin-walled workpieces.

The paper is organized as follows. In Section 2, we give a detailed description of the hardware design of the active vibration closed-loop control platform. In Section 3, the PID control system based on LABVIEW FPGA module is designed to attenuate the vibration. In Section 4, the effectiveness of the proposed control method is examined by vibration control experiments on a thin-walled alloy workpiece. Finally, conclusions are drawn in Section 5.

2 Hardware Design

A photograph of the experimental installation of the active vibration is shown in Fig. 1.The vibration of the thin-walled workpiece excited by the milling cutter is simulated using a voice coil actuator. A proper force is applied to the thin-walled aluminium alloy workpiece by the voice coil motor at the first beginning so that the voice coil motor can simulate the 'pull' behavior to compensate the vibration even though it does not stick to the workpiece.

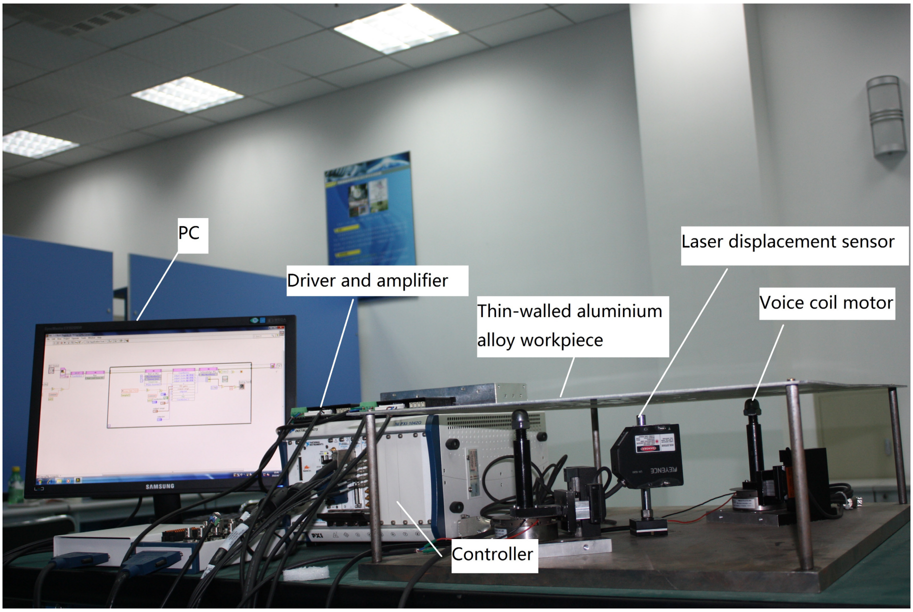

Fig. 1. Experiment platform

An illustration of the hardware designed and constructed to demonstrate the utility of active vibration control and the control system block diagram are shown in Fig. 2.The vibration of the thin-walled workpiece in milling is detected by the laser displacement sensors placed under the workpiece and sent to the FPGA analog input modules,the FPGA module processes the input signals using the control algorithm and outputs the control voltage signals to the drivers and amplifiers,which drive the voice coil motors to move up and down quickly to suppress the vibration of the workpiece.

2.1 Voice Coil Motor

In order to see the performance of voice coil motor to attenuate the vibration of thin-walled workpiece,we have to excite the thin-walled workpiece by vibration excitor,which is a good choice to simulate the vibration instead of milling cutter.The voice coil motor can also act as the vibration excitor for its excellent advantages mentioned above.The output voltage to control the voice coil excitor is given by the PXI-6733 card,which is a product produced by National Instruments(NI) and is a high-speed voltage output device that combines the latest

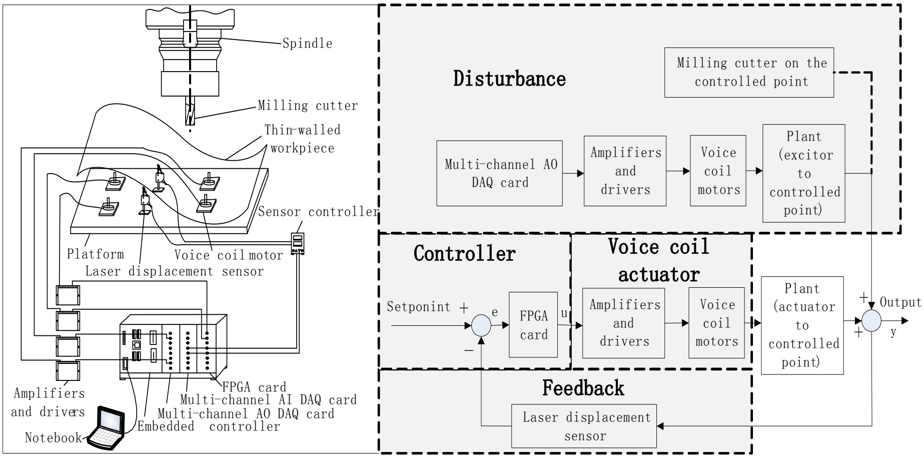

Fig. 2. Hardware configuration and control system block diagram

in PC technologies to deliver simultaneous,multichannel updates for control and waveform output applications.

Voice coil motor is a kind of direct drive device that converts electrical energy into a mechanical force[10].Its movement can be either linear or limited angle rotary motion.The advantages of voice coil motor are small size,non-commutated,quick response(within several milliseconds),high possible acceleration which is greatly suitable for fast oscillation movement(of course,the actual acceleration depends on the mass of the load being accelerated),simple control,non-backlash,good performance at low speed and long service life[11]. In our research,we apply the linear voice coil motor which utilizes a permanent magnetic field and coil winding to produce a force proportional to the current applied to the coil[12].The schematic of operating principle and structure of linear voice coil motor is shown in Fig. 3.The Lorentz force equation can be used to compute the thrust on the coil when it is electrified in the magnetic field.The thrust decides the direction of the coil's movement

$$\boldsymbol{F} = \alpha L \boldsymbol{I} \times \boldsymbol{B} \tag{1}$$

where $\boldsymbol{F}$ represents the thrust on the coil,α is the ratio of the effective length to the whole length L of the coil in the magnetic field,$\boldsymbol{I}$ is the current of the coil,and $\boldsymbol{B}$ is the magnetic flux density.When $\boldsymbol{B}$ and $\boldsymbol{I}$ are vertical to each other,the direction of $\boldsymbol{F}$ can be decided by Fleming's left-hand rule.Under this condition,(1)can be rewritten as

$$F = \alpha LIB = K_f I \tag{2}$$

where K_f is called the force constant($K_f = 21N/A$ for our voice coil motors). Thus, the thrust on the coil can be controlled by regulating the input current. Set the drivers and amplifiers at current mode so that the output current is

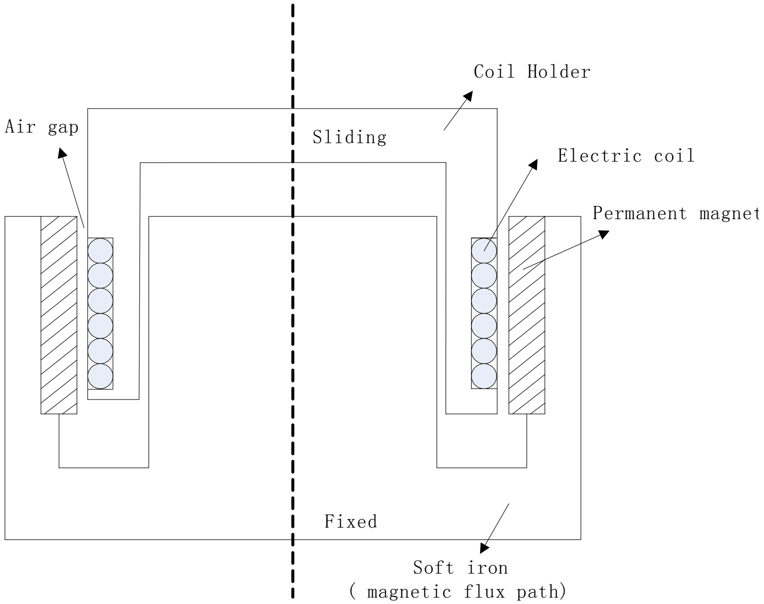

Fig. 3. Schematic of operating principle and structure of linear voice coil motor

proportional to the input voltage. And hence the current can be regulated by the control voltage signal $u(t)$. The relation between control force F(t) and control voltage signal $u(t)$ can be shown as

$$F = K_f K_a u(t) = K_c u(t) \tag{3}$$

where K_a is a constant between voltage and current($K_a = 1A/Volt$ for our voice coil motors), and K_c is a constant.

2.2 LABVIEW FPGA Module

The NI LabVIEW FPGA Module extends the LabVIEW graphical development platform to target field-programmable gate arrays (FPGAs) on NI reconfigurable I/O (RIO) hardware. LabVIEW is well suited for FPGA programming because it clearly represents parallelism and data flow, so users who are both experienced and inexperienced in traditional FPGA design can productively apply the power of reconfigurable hardware.

With the LabVIEW FPGA Module, users can:create custom hardware without VHDL coding or board design, Execute multiple tasks simultaneously and deterministically, and solve many applications, including unique timing and triggering routines, ultra high-speed control,digital signal processing (DSP), and any other application requiring high-speed hardware reliability and tight determinism.In contrast to the processors found in your PC, which run software application in predefined circuitry, programming an FPGA rewires the chip itself to implement your functionality directly in hardware.For control systems, you can run advanced control algorithms directly in the FPGA fabric to minimize latency and maximize loop rates.

LabVIEW is a highly productive language for FPGAs because it abstracts complex details for quick design time, but it retains the ability to program every clock tick when necessary.[13]With the FPGA module like PXI-7854R card we use, you configure the behavior of the reconfigurable FPGA to match the requirements of a specific control system. The VI you create to run on an FPGA target is called the FPGA VI. Use the FPGA module to write FPGA VIs. When you download the FPGA VI to the FPGA, you are programming the functionality of the FPGA target.The PXI-7854R card has eight analog inputs and eight analog outputs which is suitable for us to acquire the vibration signals and output the control signals.

2.3 Data Acquisition

Data acquisition is an indispensable part of a control system,especially for a closed-loop control system.The vibration displacement signals are acquired not only by the PXI-7854R card but also by the PXI-4472 card at the same time, which has eight analog inputs with 24-bit resolution ADCs that are simultaneously sampled at a software-programmable rate.Thus we can observe the vibration displacement signals online while controlling the vibration.

3 Control Design

NI LABVIEW FPGA module is used to design the control system that includes analog input module to get the vibration displacement signals, PID controller module, and analog output module to drive the voice coil motors. PID (Proportional-Integral-Derivative) control is the most widely used in industrial control systems. The popularity of PID controller is mostly due to its appealing characteristics such as simple architecture, easy design and parameter tuning without complicated computation[14]. The general transfer function of the PID controller is shown as follows:

$$u = K_p e + K_i \int edt + K_d \frac{de}{dt} \tag{4}$$

- ☐ K_p=Proportional gain
- ☐ K_i=Integral gain
- ☐ K_d=Derivative gain

The control system block diagram is shown in Fig. 2.The setpoint is the displacement value of the controlled point which should be zero, the variable (e)represents the error which is used to compute the output voltage signal (u) in FPGA card,an embedded controller .The signal (u) is sent to the plant(actuator

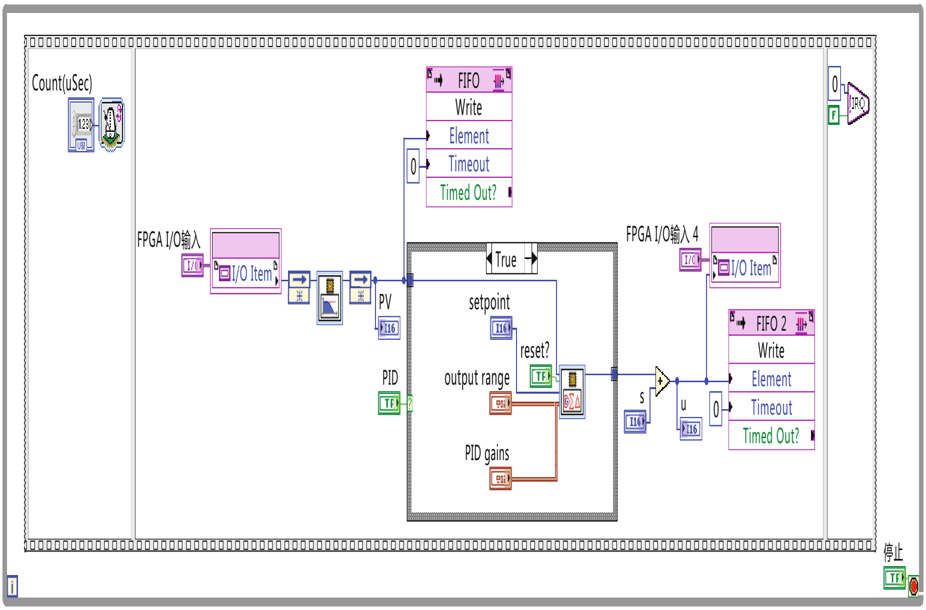

Fig. 4. The block diagram of FPGA VI

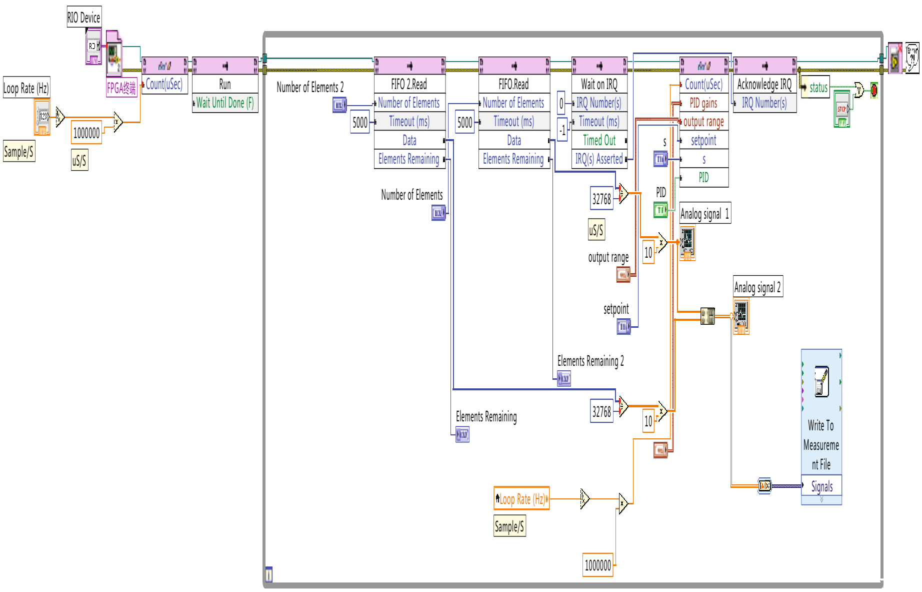

Fig. 5. The block diagram of host VI

to controlled point),and the new output (y) will be sent back to the sensor again to find the new error signal (e).The controller takes this new error signal and computes its output signal (u) again,this goes on and on until the error signal (e) equals zero[14].

On the LABVIEW FPGA platform, a LABVIEW project, a FPGA VI, and a host VI are created. The LABVIEW project is the file to manage all the VIs and the FPGA on the development computer. FPGA VI, as shown in Fig. 4, is compiled and downloaded onto the FPGA card to acquire the vibration displacement signals via the analog input modules, calculate the control signals according to the control algorithm and output the control signals via analog output modules. The host VI on PC, as shown in Fig. 5, is used to communicate with the FPGA VI and to convert the data from binary to decimal, so we can modify some important parameters such as PID parameters, loop rate and so on.

4 Experimental Test

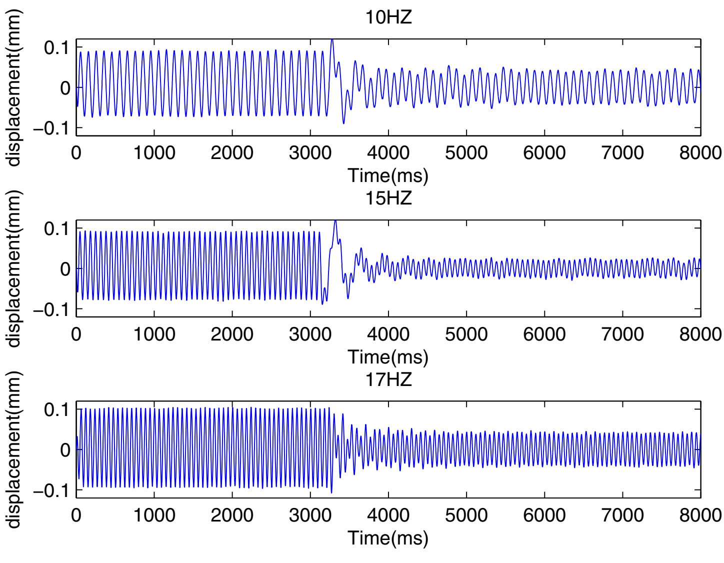

Fig. 6. Vibration signal

We choose a thin-walled aluminium alloy workpiece (3 mm of thickness) to conduct our active vibration control test. The output voltage signal to the driver and amplifier of the voice coil excitor given by PXI-6733 card is a sine wave whose amplitude and frequency can be modified via PC. The PID paraments can also be updated to control the vibration via the host VI on PC. We can see the vibration displacement via the chart whose data is acquired by the PXI-4472 card online. We carry out three tests to see the results of the active vibration control by different excited frequencies of 10Hz,15Hz,17Hz respectively. The results are shown in Fig. 6. The amplitude of the vibration can be decreased by 48%,75%,54% at excited frequency of 10Hz,15Hz,17Hz respectively.

5 Conclusion

In this paper,an active vibration control system is designed and build using NI control platform such as LABVIEW software and LABVIEW FPGA module.The experimental results presented verify that the closed-loop PID control implemented on NI FPGA module is an effective strategy to achieve the aim of active vibration control and using voice coil motor as the actuator to attenuate the vibration of thin-walled workpiece is feasible and effective.

Lacking of vacuum fixture to stick the voice coil motor to the thin-walled workpiece,we conduct the active vibration control by applying a proper force at the first beginning,which is not allowed at the actual machining.The model of thin-walled workpiece is a nonlinear system so that the PID control is limited and time-consuming.Therefore,the further work will focus on the fixture design and advanced algorithm such as predictive control,adaptive control,robust control and so on.And we can carry out the active vibration control in the practical milling even achieve the aim of chatter control in milling thin-walled workpiece.

References

1. Jenifene, A.: Active vibration control of flexible structures using delayed position feedback. J. Syst. Control Lett. 56, 215–222 (2007)
2. Tavakolpour, A.R., Mailah, M., Darus, I.Z.M., Tokhi, M.O.: Self-learning active vibration control of a flexible plate structure with piezoelectric actuator. Simulation Modelling Practice and Theory 18, 516–532 (2010)
3. Tokhi, M.O., Hossain, M.A.: A unified adaptive active control mechanism for noise cancellation and vibration suppression. Journal of Mech. Syst. Signal Process. 10, 667–682 (1996)
4. Long, X.H., Jiang, H., Meng, G.: Active vibration control for peripheral milling processes. Journal of Materials Processing Technology 213, 660–670 (2013)
5. Bisegna, P., Caruso, G., Maceri, F.: Optimized electric networks for vibration damping of piezoactuated beams. Journal of Sound and Vibration 289, 908–937 (2006)
6. Zhang, Y., Sims, N.D.: Milling workpiece chatter avoidance using piezoelectric active damping: A feasibility study. Smart Mater. Structures 14, 65–70 (2005)
7. Nagaya, K., Yamazaki, H.: Control of micro-vibration of a machine head by using piezoelectric actuators. Journal of Applied Electromagnetics and Mechanics 8, 315–326 (1997)
8. Kar, I.N., Miyakura, T., Seto, K.: Bending and torsional vibration control of a flexible plate structure using H_∞-based robust control law. IEEE Trans. Control Syst. Technol. 8, 545–553 (2000)
9. Xianmin, Z., Changjian, S., Erdman, A.G.: Active vibration controller design and comparison study of flexible linkage mechanism systems. J. Mech. Mach. Theory 37, 985–997 (2002)

10. Zhang, D.W., Feng, X.M.: The technical principle of voice coil actuator. The Journal of Zhongbei University 27(3), 224–228 (2006)
11. Chu, L.X., Lin, H.: The linear position tracking servo system using a linear voice-coil motor. Academic Journal of Xi'an Jiaotong University 20(3), 164–167 (2008)
12. Chen, Y.D., Fuh, C.C., Tung, P.C.: Application of voice coil motors in active dynamic vibration absorbers. IEEE Transactions on Magnetics 41(3), 1149–1154 (2005)
13. National Instruments for FPGA information, `http://www.ni.com/labview/fpga/`
14. Ali, F.H., Mahmood, H.M., Ismael, S.M.B.: LabVIEW FPGA implementation of a PID controller for D.C. motor speed control. In: 2010 1st International Conference on Energy, Power and Control (EPC-IQ), pp. 139–144. IEEE Press, Basrah (2010)