Design of Three-axis ED Milling Machine Based on the PMAC Motion Card

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Abstract—**This paper presents a new three-axis ED milling machine, which is based on the PMAC motion card. The machine is composed of the motion system, the control system, the working fluid supplying system and the EDM pulse generator. First, the motion system , the working fluid supplying system, the hardware of the control system, and the EDM pulse generator have been built, then the software system of the industrial computer has been developed based on the Visual Basic 6.0 in order to control the machine and monitor the status of the machine. Using the PMAC motion card, the servo control program, the decoding program and the PLC program have been programmed. The software system of the EDM pulse generator is implemented based on a good real time operating system called µC/OS-II, and the software system is composed of three main tasks, namely the data processing task, the communication task and the monitoring task. The milling experiments have been carried out on the ED milling machine based on the PMAC motion card, and the results show that the ED milling machine is steady and reliable when milling with three-axis.**

Index Terms— **ED milling; PMAC; EDM pulse generator; real time operating system**

I. INTRODUCTION

Electrical discharge machining (EDM) is a processing method of transforming electric energy into heat energy with the pulse voltage added between the workpiece and the electrode, so it can remove the material from the workpiece [1]. As a non-traditional material removal process, EDM has long been employed in manufacturing of molds, as well as in automotive, aerospace and surgical components due to its unique merit of machining by thermal-mechanical effect regardless of the hardness of the materials [2]. EDM has been developed in the late 1940s, and it does not make direct contact between the workpiece and the electrode, as a result, it can eliminate the effect of the mechanical stresses, chatter and vibration problems.[3-5].

Electrical discharge (ED) milling is an evolution of CNC contouring EDM [6-7]. A rotating cylindrical electrode follows a programmed path in order to obtain the desired shape of a part, like a cutter used in

conventional computerized numerical controlled (CNC) milling. Compared to traditional sinking EDM, the use of simple electrodes in ED milling eliminates the need for customized shaped electrodes [8-11]. In the ED milling, the simple shape electrode does layer-by-layer milling to get a three-dimensional complex parts, at the same time, electrical discharges occur repeatedly to remove materials along the programmed path. According to the discharge status between the electrode and the workpiece, the control system determines the forward and withdrawal feedrate of the electrode, as a result, a dedicated ED milling control system need to be developed to control the ED milling and edit motion program. Ref. [12] used one kind of milling EDM control system, a discharge power supply provided the power for the system, the computerized numerical controller interpolated algorithm in the interrupt service routine, which was triggered in the fixed time. The feedrate was determined by a gap controller, which maintained the discharge in the gap, the interrupt service routine modified the current position of the electrode on the main axis. Ref. [13] designed a new control system for a micro-ED milling machine. The motion system was made up of three-axis rotary motor driven linear stages and a spindle motor. They were controlled by a motion controller board installed on a control PC, one data acquisition board and one analog image acquisition board were installed in the control PC, a vision system monitored the electrical machining condition , which was represented by the behavior of the gap voltage and current during the EDM process. The data acquisition board countered the number of discharge pulses in real time.

In this study, a new kind of three-axis ED milling machine based on the PMAC motion card has been designed. After building the motion system and the working fluid supplying system, the Microsoft Visual Basic 6.0 is used to build the software system of the industrial computer. The software system of the PMAC motion card is developed. Then, based on the µC/OS-II, the EDM pulse generator software system is developed, which contains three main tasks, due to the well real time performance, the EDM pulse generator can bear more

work than the traditional pulse generator, as a result, the hardware of the system is simplified. Finally, some milling experiments have been carried out, and the new ED milling machine is proved to be stable and reliable. The article is structured as follows: Section I introduces the principle of ED milling and the research status. Section II describes the design of the motion system and the working fluid supplying. Section Ⅲ describes the software system of the control system, including the the industrial computer, the PMAC motion card and the EDM pulse generator. Section Ⅳ introduces some ED milling experiments carried out by the ED milling machine with different axes. Section Ⅴ summarizes the article.

II. DESIGN OF THE MACHINE TOOL

The structure of the ED milling machine is shown in Fig. 1. The machine is composed of four main elements, namely the motion system, the working fluid supplying system, the control system, and the EDM pulse generator. The photograph of the ED milling machine is shown in Fig. 2.
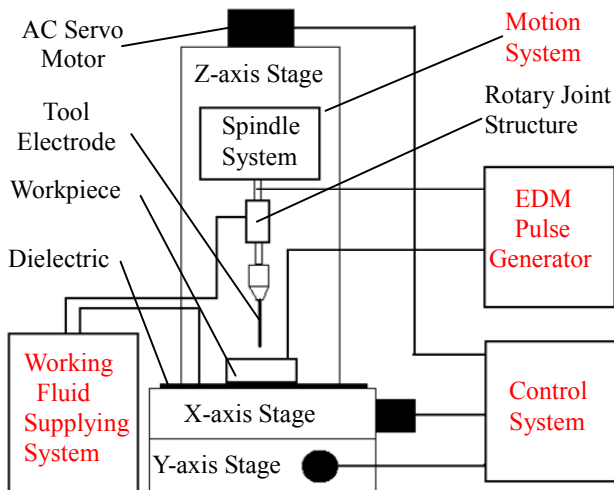

Figure 1. Structure of the ED milling machine.

Fig 2. Photograph of the ED milling machine.

A. Design of the Motion System

The photograph of the motion system is shown in Fig. 3. The motion system plays a key role in a machine tool, which will carry out the command of the control system, it is absolutely necessary. The machine tool is C-type structure in this design. The motion system is composed of the X-axis stage, the Y-axis stage, the Z-axis stage, and the spindle system. The movement is controlled by the AC servo motors, and the servo motor of the Z-axis has more power than other servo motors, as it must driver the Z-axis smoothly to overcome the gravity of the Z-axis stage. When the machine tool is shut down, a normally closed electric clutch will hold the servo motor of the Z-axis. The position loop of the machine tool is semi-closed loop, which is made of the digital incremental encoder fixed at the end of the servo motor. The spindle system provides the rotation for the electrode, which is composed of the AC motor, the AC inverter, the collecting ring, and the brush. The spindle motor fixed at the Z-axis stage is surrounded by the dielectric to prevent the discharge current from damaging the machine tool, the collecting ring and the brush will import the discharge current to the AC motor shaft. The AC motor is added to provide rotation of the electrode, with the help of the AC inverter, the speed of the AC motor is 0-3000rpm. The stage which loads the workpiece is covered with dielectric in order to prevent the discharge current from damaging the machine tool.

Fig 3. Photograph of the motion system.

B. Design of the Working Fluid Supplying System

There are three basic types of flushing in the ED

milling, and they are side flushing, electrode injection flushing and electrode suction flushing, Ref. [14] found that an optimized flushing pressure and electrode rotation can achieve an approximately constant cutting feed rate, and the electrode injection flushing and wider working range of flushing pressure can get higher material removal rate(MRR) value than the side flushing and the suction flushing. The MRR, the electrode wear rate (EWR), surface roughness (SR) and cutting feed rate all increase with increased flushing pressure, indicating that superior performance may be obtained from a higher flushing pressure during machining.

In this study, a new working fluid supplying system is designed in order to adjust the pressure and achieve the injection flushing. The system is made of the circulatory pump, the filter, the AC converter, the pipeline, and the rotary joint structure. The flushing pressure is adjusted by the circulatory pump controlled by the AC converter. The pipeline connects the pump and the rotary joint structure to transport the working fluid cleaned by the filter. The cutaway view of the rotary joint structure is shown in Fig. 4, the holder connects the rotary joint structure to the Z-axis stage to stop it from rotating. A threaded hole is designed on the shell of the rotary joint structure in order to connect the pipeline and seal the working fluid. There is a ring groove on each side of the threaded hole to hold the O-ring. In this design the maximum pressure of the working fluid is 1MPa, the maximum speed of the shaft is 3000rpm, the inner diameter of the O-ring is 20mm, the diameter of the shaft is 19.4mm, and the diameter of the ring groove is 20mm. A ring groove on the shaft is designed to store the working fluid to prevent the pressure fluctuation. The photograph of the rotary joint structure is shown in Fig. 5.
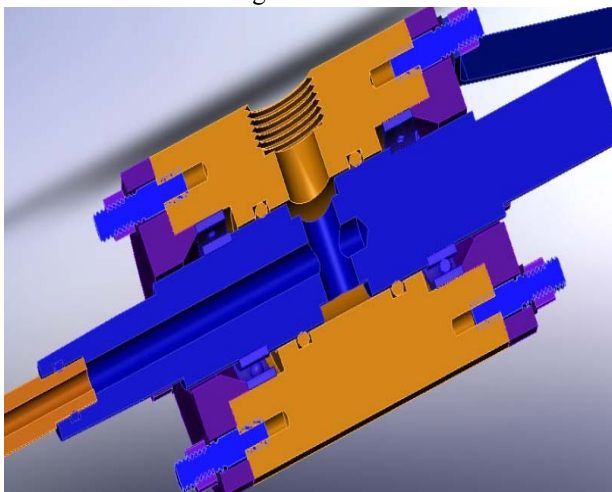

Fig 4. Cutaway view of the rotary joint structure.

III. DESIGN OF THE SOFTWARE SYSTEM

The control system structure of the ED milling machine is shown in Fig. 6. As shown in Fig. 6, the control system structure is master slave module, the industrial computer is the master, in this control system, the slave must have good real-time performance, so it is formed by the PMAC motion card and the micro control

unit (MCU) of the EDM pulse generator. The industrial computer transfers commands and files to the PMAC motion card via the Ethernet. The PMAC motion card sends the analog signal to the AC servo motor drive of the X-axis stage, the Y-axis stage, and the Z-axis stage, also it control the AC converter of the spindle and the filter system with analog signals. Some digital input-output signal is pressed by the PLC connected to the PMAC motion card. Commands such as the pulse on-time, the pulse interval time are downloaded to the MCU of the EDM pulse generator by the industrial computer via the RS232, the discharge status between the workpiece and the tool electrode is collected by the analog to digital converter, and it is send to the industrial computer through the USB. The software structure of the control system is shown in Fig. 7.

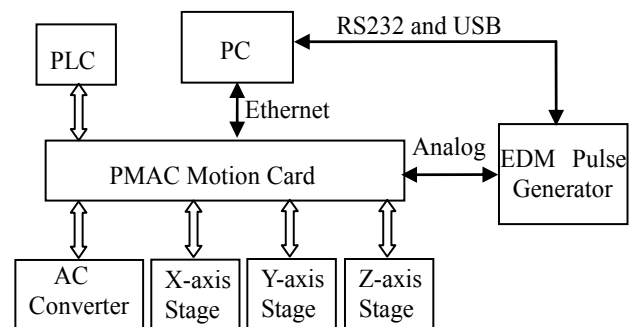Fig 5. Photograph of the rotary joint structure.
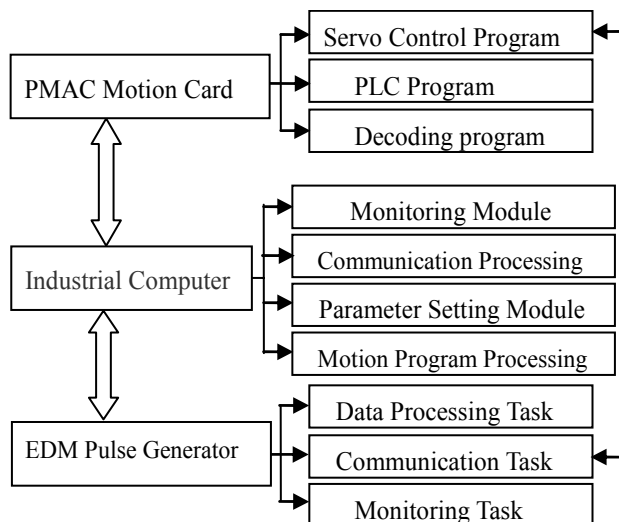

Fig 6. Structure of the control system.

Fig 7. Structure of the software system.

(a)   Editing mode

A. Software System of the Industrial Computer

The industrial computer is the master computer, which plays a key role in the control system, it must complete some important function such as the human machine interface and the management of the background task. All the programs of the master computer are developed in the Windows environment, and they are programmed based on the Visual Basic 6.0. All of the programs have less demand of real-time, as a result, the industrial computer is not able to collect the discharge status and process the motion programs. The software system is made of four main modules, the monitoring module, the communication processing module, the parameter setting module, and the motion program processing module. The monitoring module plays an important role in the human machine interface, it processes the information coming form the EDM pulse generator and the PMAC motion card, and it displays the voltage waveform, the current waveform, the status of the motion card, and the running status of the PLC, it makes the user to better understand the current status of the machine. The communication processing module establishes the communication between the master and the slave, and receives the signal from the slave. The parameter setting module sets the parameter of the PMAC motion card to finish the configuration, and it sets the parameter of the EDM pulse generator, such as the open voltage, the peak current, the pulse on-time, and the pulse interval time, the parameter setting module also determines some machining parameters according to the material of the workpiece. The motion program processing module finishes the editing of the motion program, it transforms the motion program edited by the user into the file, which can be recognized by the PMAC motion card, at the same time it examines the motion program to avoid the syntax error. Different user interfaces of the industrial computer are shown in Fig. 8.

(b)   Manual operation mode

(c)   Manual operation mode

Fig 8. Different user interfaces of the industrial computer.

B. Software System of the PMAC Motion Card

As the core element of the control system, the PMAC motion card should be competent for the control of the motion system, the AC converter, and some other function of the PLC, so it should be able to finish the real-time task. The structure of the software system of the master computer is shown in Fig. 7. The software system of the PAMAC motion card is made of three programs,

namely the PLC program, the servo control program, and the decoding program. The PLC program will process the digital input-output signal of the machine. It collects the signal of the keyboard on the control panel, and controls the auxiliary equipment, such as the working fluid, and the electric clutch of the Z-axis stage. The PLC program can also achieve to control the ED milling machine with the handwheel. The servo control program determines the feed rate of the motion system according to the analog signal from the EDM pulse generator, the flow diagram of the servo control program is shown in Fig. 9. The decoding program decodes the G-code, the M-code, and the S-code in the motion program edited by the user, and then it converts those codes into the code that the PMAC motion card can recognize.
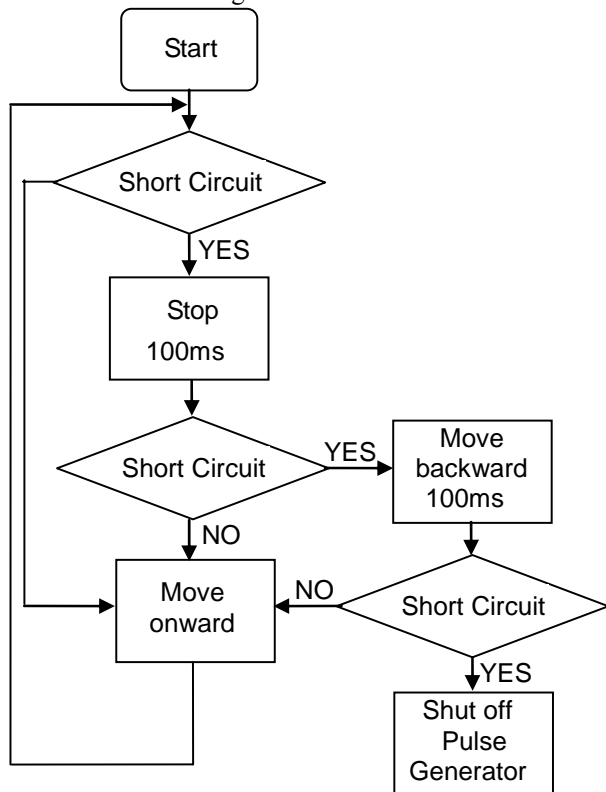

Fig 9. Flow diagram of the servo control program.

C. Software System of the EDM Pulse Generator

In this control system, in addition to the traditional functions, such as controlling the peak current, the open voltage, the pulse on-time, and the pulse interval time, the EDM pulse generator is able to realize the data processing of the discharge status and the communication function. In the MCU of the EDM pulse generator, the real time operating system μC/OS-II has been transplanted to ensure the stability of the system. Three tasks, such as the monitoring task, the data processing task, and the communication task, are established. The monitoring task collects the discharge status through the analog to digital converter, and it completes self-diagnosis to protect the EDM pulse generator. The data processing task processes the data from the monitoring task, the feed rate of the motion system is calculated by an algorithm programmed in this task to maintain the

discharge. The communication task transports the feedrate of the motion system calculated by the data processing task to the PMAC motion card through the digital to analog converter, and it also sends those discharge status data to the industrial computer through the USB. The relationship between the three tasks is shown in Fig. 10. It can be seen that the monitoring task and the data processing task are connected by the timeout message queues to monitor the system in real-time, the data processing task and the communication task are connected by the mailbox, and the interrupt service routine is programmed in order to receive the command from the RS232.
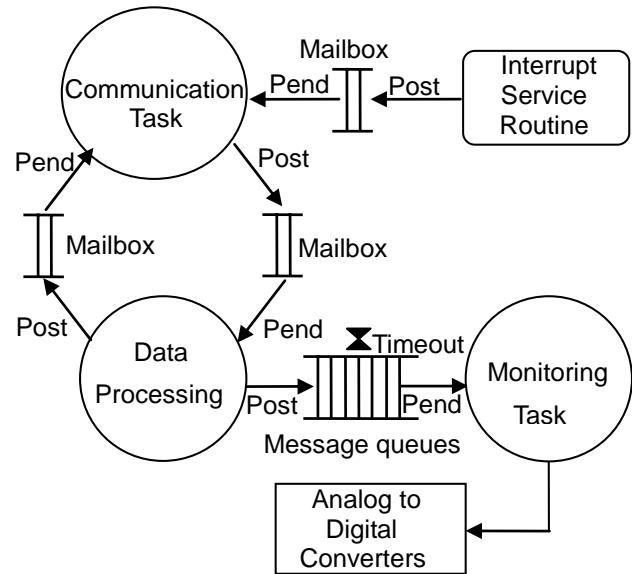

Fig 10. Relationship between the three tasks.

IV. EXPERIMENTS

Some ED milling experiments have been carried out to estimate the stability and the reliability of the designed ED milling machine. In the experiments, the tool electrode is the hollow-tube copper with the outer diameter of 10mm and the inner diameter of 5mm, the working fluid is emulsion. The photograph of the workpiece machined by the ED milling machine with different axes is shown in Fig. 11.
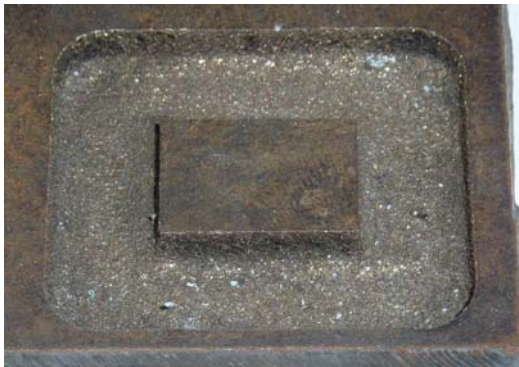
V. CONCLUSION

Based on the PMAC motion card, the three-axis ED milling machine has been designed. The motion system, the control system, the working fluid supplying system, and the EDM pulse generator are designed. The software system of the industrial computer is developed based on the Visual Basic 6.0. Using the PMAC control card, the PLC program, the servo control program, and the decoding program are developed. The real time operating system μC/OS-II has been transplanted to ensure the stability of the system. According to this paper, the following conclusion can be drawn:

(1) The designed three-axis ED milling machine is able to machine the workpiece steadily and reliably during three-axis ED milling.

(2) In the working fluid supplying system, the AC converter is able to control the pressure of the working fluid through changing the rotation speed of the circulatory pump. The rotary joint structure can achieve electrode injection flushing, and the rotation of the electrode tool.

(3) The control system of the EDM pulse generator is able to finish multitask after the transplanting of the real time operating system due to its good real time performance. The calculation of the feed rate in the data processing task reduces the work load of the PMAC motion card, and more complex algorithm can be programmed in the data processing task.

(a) Single-axis

(b) Two-axis

(c) Three-axis

Figure 11. Photograph of the workpiece machined by the ED milling machine with different axes.

REFERENCES

[1] F. Z. Han, L. Chen, D. W. Yu and X. G. Zhou, "Basic study on pulse generator for micro-EDM," *Int J Adv Manuf Technol*, vol. 33, no. 5-6, June. 2007, pp. 474-479, doi: 10.1007/s00170-006-0483-9.

[2] F. Z. Han, Y. X. Wang and M. Zhou, "High-speed EDM milling with moving electric arcs," *Int J Mach Tools Manuf*, vol. 49, no. 1, January. 2009, pp. 20-24, doi: 10.1016/j.ijmachtools.2008.08.005.

[3] M. A. Norliana1, S. Darius G and F. B. Md,. "A review on current research trends in electrical discharge machining (EDM)," *Int J Mach Tools Manuf*, vol. 47, no. 7-8, June. 2007, pp. 1214-1228, doi: 10.1016/j.ijmachtools.2006.08.026

[4] K.H. Ho and S.T. Newman, "State of the art electrical discharge machining (EDM)," *Int J Mach Tools Manuf*, vol. 42, no. 13, pp. 1287-1300, doi: 10.1016/S0890-6955(03)00162-7.

[5] S. Singh, S. Maheshwari and P.C. Pandey, "Some investigations into the electric discharge machining of hardened tool steel using different," J Mater Process Technol, vol. 149, no. 1-3, pp. 272-277, doi: 10.1016/j.jmatprotec.2003.11.046

[6] J. P. Kruth, B. Lauwers, and W. Clappaert. "A study of EDM pocketing," Proceedings of the ISEM, Magdeburg. Germany, May, 1992, pp.271-294.

[7] J. P. Kruth, and P. Bleys. "Machining curvilinear surfaces by NC electro-discharge machining." *Proceedings of the Second International Conference on MMSS*, Krakow. Poland, September, 2000, vol. 4, pp. 31-40.

[8] P. Bleys, J.-P. Kruth and B. Lauwers, "Sensing and compensation of tool wear in milling EDM," *J Mater Process Technol*, vol. 149, no. 1-3, June. 2004, pp. 139-146, doi: 10.1016/j.jmatprotec.2003.11.042.

[9] Y. F. Chang and R. C. Hong, "Parametric curve machining of a CNC milling EDM," *Int J Mach Tools Manuf*, vol. 45, no. 7-8, June. 2005, pp. 941-948, doi: 10.1016/j.ijmachtools.2004.10.011.

[10] Z. Y. Yu, T. Masuzawa and M. Fujino, "Micro-EDM for three-dimensional cavities - development of uniform wear method," *CIRP Ann Manuf Technol*, vol. 47, no. 1, 1998, pp. 169-172, doi:10.1016/S0007-8506(07)62810-8.

[11] K. P. Rajurkar and Z. Y. Yu, "3D micro-EDM using CAD/CAM," vol. 49, no. 1, 2000, pp. 127-130, doi:10.1016/S0007-8506(07)62911-4.

[12] Y. F. Chang and R. C. Hong, "Parametric curve machining of a CNC milling EDM," *Int J Mach Tools Manuf*, vol. 45, no. 7-8, June. 2005, pp. 941-948, doi: 10.1016/j.ijmachtools.2004.10.011.

[13] J. W. Jung, Y. H. Jeong, B. K. Min and S. J. Lee, "Model-based pulse frequency control for micro-EDM milling using real-time discharge pulse monitoring," *J Manuf Sci Eng Trans ASME*, vol. 130, no. 3, June. 2008, pp. 0311061-03110611, doi: 10.1115/1.2917305.

[14] B, H, Yan and C, C, Wang, "The machining characteristics of Al2O3/6061Al composite using rotary electro-discharge machining with a tube electrode," *J Mater Process Technol*, vol. 95, no. 1-3, October. 1999, pp. 222-231, doi: 10.1016/S0924-0136(99)00322-2.

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