Core Technologies of Next-generation Machine Tools

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Abstract

This paper described the current status of machine tool technology and its future trends with a particular emphasis on high-speed machining. People in machine tool industry have continuously sought to serve fast-changing manufacturing industry with economical machining solutions. At present, it appears that more productivity gain is demanded to shorten time-to-market and machining requirements become more stringent. In this regard, this paper firstly addressed a high-speed spindle as a key element for the next-generation machine tools. The sequel to it apparently went to high-speed feed axes and final discussion included the problem of how to optimize overall system including servo function. Lastly a brief look to NC technology including machine intelligence was taken.

Key Words: Next-generation machine tools, High-speed machining, High-speed spindle, High-speed feed axes, NC technology, Machine intelligence

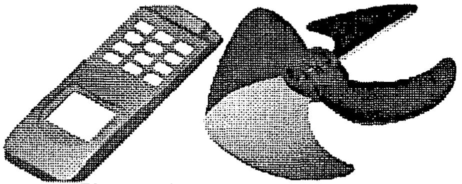
1. Introduction

Machine tools, as essential elements of many manufacturing systems, play vital roles in manufacturing industry and make highly sophisticated machining operations possible in conventional shop floor environments. It appears that machine tools are now on the verge of a radical change towards putting higher standing on operating performance as shown in Table 1[1].

Table 1 Trends in Machine Performance

	1960	1970	1980	1990	2000
Feed (m/min)	5	10	20	75	120
Acceleration (g)	0.2	0.2	0.6	1.5	2
Rotary Axis (rpm)	2	4	8	33	45
Spindle (rpm)	4 k	6 k	15 k	40 k	60 k
Tool Change (s)	30	10	2	2	1
Accuracy (μm)	50	25	13	2	1
Repeatability(μm)	25	13	7.6	1	0.5

That is, desired performance level becomes tougher and stricter, so in some cases conventional machine tool technology cannot meet it. To become more realistic, take a look at parts shown in Fig. 1.



(a) Phone body (b) Fan

(c) Precision Mold (d) Complex Machining

Fig. 1 Sample Parts

(a) and (b) show typical parts used in computer and communication industry, which require higher precision figure on the order of 1/100mm as well as good surface roughness in their mold machining. In addition, machining time should be short because time-to-market is critical in that industry. (c) is a mold to produce rubber alphabet signs. It takes only half a day to machine this complex mold with today's high performance machining center. Meanwhile, (d) is a bit different example, which requires integrated machining operation such as mill-turn with *Y*-axis movement in CNC lathes to reduce set-up time. This sort of parts can be machined in integrated process machines such as shown in Fig. 2. Now it becomes more evident that next-generation machine tools should have differentiated and higher performance from the past ones.

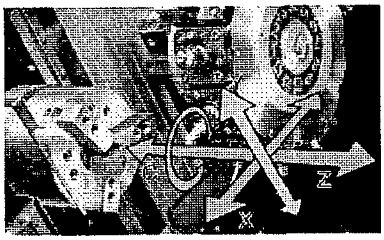


Fig. 2 Example of Integrated Process Machinery

2. Race against Speed

2.1 Needs for High-speed Machines

From the early 1990s and to date, the top technical issue in machine tool industry has been how to increase the speed of linear and rotary motion mechanisms. The early trials included such mechanisms as NC lathe turrets and ATCs (automatic tool changers), which contribute to non-cutting operation time. Soon, end users realized that the time taken for pure cutting operation became a dominant factor in increasing productivity as the speed of turrets and ATCs increased. Fig. 3 shows dramatic decrease in positioning time by increasing acceleration as well as traverse speed. Reduction in pure cutting time, the main topic in this section, is encompassed with a wide variety of engineering disciplines and even brings about changes in organization structure. Along with advances in cutting tool materials, machine tools themselves are undergoing a radical change that they have to perform equally or even better at the higher cutting speed exceeding 200m/min.

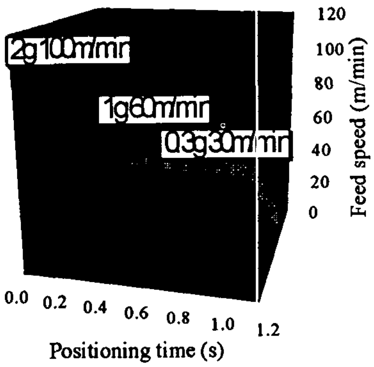


Fig. 3 Decrease in Positioning Time

Besides increase in productivity with the help of high-speed machines, end users are also fond of beneficial effects inherent to high-speed cutting mechanism, such as increase in machining accuracy by reduction in cutting force and heat, easy chip disposal, and easy chatter avoidance.

2.2 High-speed Spindles

Needless to say, the core technology of high-speed machines is their spindles that can withstand at high rotational speed well above 12,000rpm. Fig. 4 shows a typical arrangement of high-speed spindles composed of front and rear bearings, built-in motor, cooling jacket, and draw bar for chucking tools. This 12,000rpm spindle has a high sales record in Daewoo.

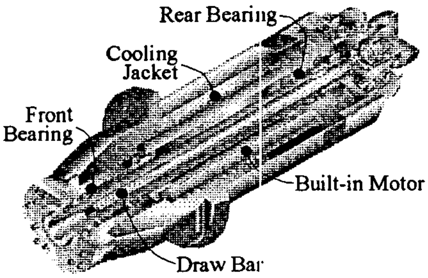


Fig. 4 Typical high-speed Spindle

Nowadays, it is not difficult to find spindles that exceed 2 millions in DN value. The recent advances in lubrication technology make it possible to manufacture high-speed spindles having high reliability. The most remarkable technical breakthrough was the adoption of hybrid ceramic bearings to machine tools. Due to their high stiffness to mass ratio, ceramic bearings have many technical advantages over steel bearings so that they now become a key element in high-speed spindles together with special lubricant delivery methods, which include air-oil lubrication, oil-jet lubrication and under-race lubrication.

Currently, the under-race lubrication method allows machine-tool spindles to withstand at the highest possible DN value over 3 millions. One example is shown in Fig. 5, which depicts a 35,000rpm spindle under development in Daewoo incorporating air-oil under-race bearings from NSK. When designing high-speed spindles, we have to take a serious consideration on the initial amount of preload applied on bearing pairs and its changes during operation. Unless a sophisticated cooling method is applied, constant-pressure preload is the only way to reliable operation above 20,000rpm. In addition, high balancing quality is essential to minimize unwanted tool vibration.

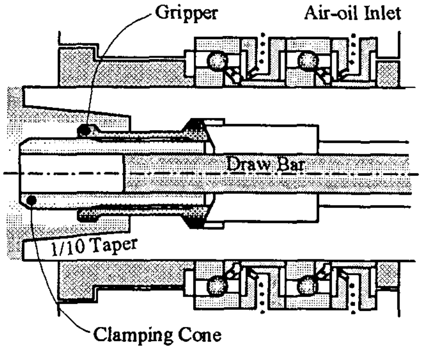


Fig. 5 35,000rpm Spindle

Non-contact bearings, using fluid film or magnetic levitation, are another excellent candidate for high-speed spindles. In many situations where extraordinary high-speed is necessary, there is no other choice without them. For example, we are going to apply an aerostatic spindle to a precision mold center, which requires 50,000rpm.

Another important and practical technical issue is the spindle nose interface that holds tools. Currently, there are two options to choose from, that is long 7/24-steep or 1/10 short taper. One form of the long taper interfaces widely used is the BT(British Taper) interface. Though it keeps tools rigid and concentric to spindles at the conventional rotating speed range, it is prone to expand or give clearance at high rotational speed so that vibration and positional deviation of tools can occur. In order to overcome such problems, short taper interfaces having two contact surfaces were devised, and one representative example is the HSK(Hollow Short Taper) interface, originally designed in Germany. The spindle in Fig. 5 has the HSK tool interface.

2.3 Actuators

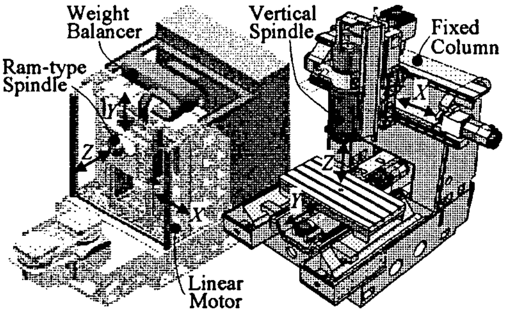
Since the first machine tool appeared, little changes have been made in linear feed axis mechanisms, in a sense that still screw mechanisms are widely adopted even in the state-of-the-art machines. One reason is due to the fact that screw feed mechanisms have two functions: the first is motion conversion function that converts rotary motion to linear motion with high efficiency; the second is scale function inherent to screws having known leads. The quality of a ball screw is classified by the accuracy of the lead provided.

In cases where high-speed feed axes are necessary, however, ball screws are vulnerable to vibration because of their long or slender structure. Pioneered by Anorad[2], applying linear motors to feed axes showed an outstanding performance leap such as shown in Table 2(based on Fanuc data), which completely removed mechanical transmission elements between actuators and moving tables resulting in stiff feed axes showing very little backlash.

Table 2 Ball Screw vs Linear Motor

	Ball Screw	Linear Motor
Max speed(m/min)	90	200
Max acceleration(g)	1.5	2
Stiffness(kgf/µm)	~10	~20
Settling time(ms)	100	10-20
Max force(N)	26,700	9,000/coil
Reliability(hrs)	6,000-10,000	50,000

Fig. 6(a) depicts a high-speed machining center having linear motors in all axes under development. One drawback of linear motors is their poor continuous thrust force so that a weight balancer is recommended for vertical axes such as shown in Fig. 6(a), while an already-developed high-speed vertical machining center (Fig. 6(b)) having a 20,000rpm spindle and 40m/min ball-screw axes does not use any balance mechanism for better servo performance.



(a) Horizontal Type (b) Vertical Type

Fig. 6 High-speed Machining Centers

Many studies on ball screws have been made to compete with linear motors over the last 3 years, and now maximum traverse speed of 60m/min can be easily achieved in contrast with 120m/min, typical maximum speed of linear motors. Though we can build high-speed axes by using ball screws capable of running at high DN value well over 100 thousands, heat generation should be carefully considered to protect from thermal jamming, a catastrophic failure. One solution to this problem is to use hollow ball screws equipped with paths for cooling medium. A machine shown in Fig. 7 has such ball screws equipped in all axes and we could also achieve a dramatic decrease in thermal expansion of ball screws. The rapid traverse speed of this machine is 60m/min.

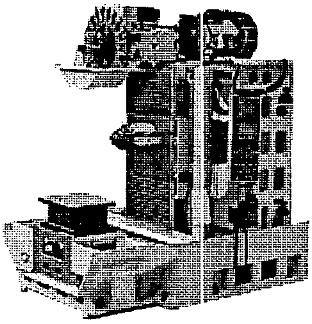


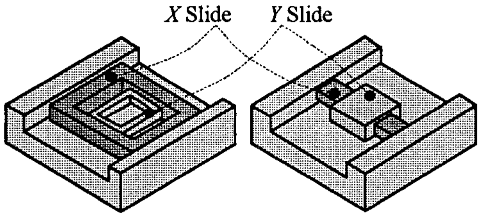
Fig. 7 High-speed Line Center

2.4 System Optimization

High-speed machines are dynamic in nature, which means all the elements should function in a close coordination with each other. We have to pay for the price in making high-speed spindles or feed-axes, that is many constraints are superimposed to different machine units at the same time. The first constraint we have to consider is the inertia of every moving element. The second is high power consumption. As the speed of machine tools increases, the power required does not increase linearly, but exponentially. Such environmental effects as noise or various kinds of fluid mist should be also considered. Lastly, cost: this governs everything in real world. We can achieve all the necessary high-speed function with ease if cost involved is considered to be secondary, but cost often becomes the most important element in development of a new machine tool. We are always observing that low-cost, economical machines with just necessary function have constant, fairly good sales records. Although it is not easy to design the best, optimized machines with an affordable price tag under such constraints, these measures can be employed.

We identified that proper selection of spindle specifications allows us to deploy high-speed function with minimum efforts. For example, high torque characteristics were necessary when designing the machine in Fig. 6(b) intended to use for mold machining. The first difficulty was how to manage the massive Z-axis carrying a big built-in motor in fast moving traverse conditions within specified accuracy. There still seems to be no other optimum solution without light Z-axis structure by replacing the comparatively big built-in motor.

One structural approach resulting in high-speed machines is to take lightweight axis configurations shown in Fig. 8 into consideration. Many high-speed horizontal machining centers now make use of open-frame axis configuration depicted in Fig. 8(a), which has one primary sliding body and completely enclosed another parasitic body moving in a different direction on the same plane. The machines shown in Fig. 6(a) and Fig. 7 adopt this configuration. With this axis arrangement, the width of a machine can be considerable due to the large X-axis slide body.



(a) Open frame (b) H frame

Fig. 8 Lightweight Axis Configuration

In this case, we can also consider another configuration shown in Fig. 8(b), referred to as *H*-frame. Contrary to open-frame, the secondary, parasitic slide body is guided by sides of the primary yielding a smaller footprint.

When talking about optimization of engineering problems, we often get engaged into simulation work because many variants should be generated and compared with each other to result in the best optimum solution. Simulation technology such as FEM is now indispensable in development of a new machine tool. We can quickly evaluate many "what-if" questions arising from design process, and thereby we can shorten lead-time and eliminate bad designs.

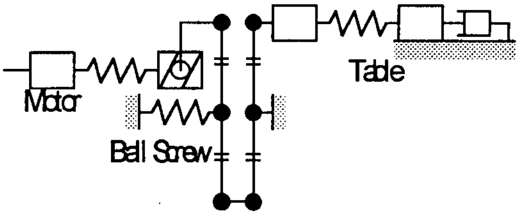


Fig. 9 Dynamic Model of Feed Axes

The ideal first step would be constructing a mechanical multi-body model shown as Fig. 9[3], and then it is inserted to a servo control loop in order to figure out servo performance in advance. This process assures that a new design conforms to specified fast machining performance and evaluates almost every major machine element. Well-performed simulation results in coordinated, fast servo response with sharp cornering characteristics down to the level of a few micrometers.

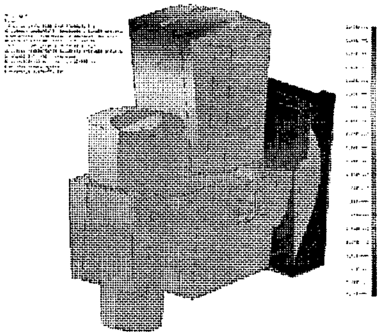


Fig. 10 Normal Mode Dynamics Simulation

The following step is to deal with each structural part to verify how well each part behaves under specified operating range. One important simulation is natural frequency evaluation such as shown in Fig. 10. This sort of FEM simulation is well established so that we can easily identify mechanical and thermal weak points. The last measures are considered to be adopting light structural materials, which always bring about cost burden. However, aluminum and epoxy-based materials become popular in special machinery such as the mold center stated before.

3. Numerical Control Technology

Since Cincinnati manufactured the first NC mill for machining airplane wing components in 1952, many complex mechanical mechanisms have been replaced with electronic servo devices and several machining processes can be integrated into one machine in a comparatively easy way. The essence of numerical control lies on its position control function. Fig. 11 shows the functional blocks of the semi-open Daewoo 380Mi NC, whose MMI(man-machine interface) platform is based on PC architecture. PC-architecture rapidly becomes popular as a basic hardware platform of NC, even by the major NC makers such as Fanuc and Siemens due to its flexibility, ease of deployment and low cost, regardless of needs of open architecture.

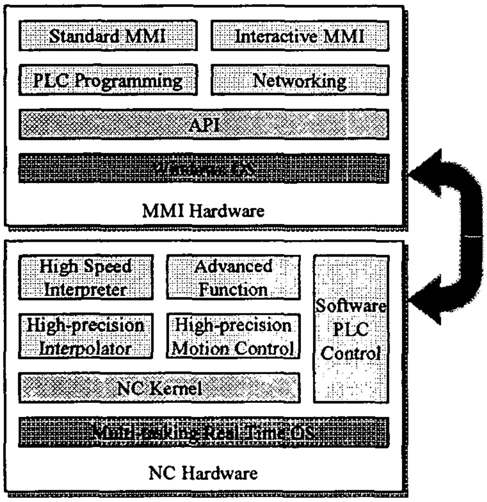


Fig. 11 Functional Blocks of Daewoo 380Mi NC

Position control in the NC hardware starts from interpreting G-code NC programs entered in the MMI hardware through standard MMI editing function or interactive part programming MMI function, and then closely coordinated motion profiles are generated in the interpolator module. In this course, we are interested in how much fast G-codes are processed and how much frequently new positions are commanded and compared with current positions. The 380Mi NC can process position command generation every 1ms and this cycle time is fundamental in achieving high-speed machining. Long cycle time results in frequent stops of axes during machining and produces periodic cutter marks. Some NCs are equipped with 64-bit microprocessors to shorten the cycle time down to sub-millisecond level. Besides such short cycle time, in order to reduce shocks from abrupt changes in traverse speed, modern NCs have an interpolator capable of managing bell-type acceleration profiles.

While G-codes are basic to today's NC program, another alternative is currently on study internationally, which makes use of the STEP standard[4] The STEP standard addresses all the necessary engineering data of a product through its life cycle including machining data and thus we can directly use the STEP representation of a part in machining if a NC controller has a STEP data interpreter.

Being generated by the interpolator, the position commands are then processed by the high-precision motion control module, which generates current commands to servomotors through velocity control loop and subsequent current control loop. In doing so, advanced functions such as feed-forward control, low-pass filtering and quadrant protrusion compensation are often applied. We identified that for the best servo performance robustness to load variations is important in high-speed servomechanisms. In cases where other maker's NC is used, the only possibility is to widen the bandwidth of velocity control loop, but with our own NC the lowest level of servo-control, i.e. current control characteristics, can be easily accessed and optimized for a particular machine, and thereby a great deal of burden in mechanical design can be relieved.

The MMI hardware using Windows APIs retrieves and transmits NC data via shared memory with the NC module, which is based on a real-time operating system for tight task scheduling. This sort of NC architecture has one drawback, i.e. frequent inter-communication tasks between two distinct operating systems can degrade overall performance of a NC controller. Therefore, it is necessary to manage all the major modules in one operating system so that every software module can equally access hardware resources without any delay and forthcoming open-architecture controllers can be realized more efficiently.

In addition, recent advances in manufacturing engineering call for more integrated manner in manufacturing and many CNC controllers now have industry-standard networking capability at the hardware level such as TCP/IP. For the transparent integration of manufacturing organizations with tools from CAD/CAM/CAE/PDM, even NC controllers are requested to accept the vendor-neutral STEP standard as stated before.

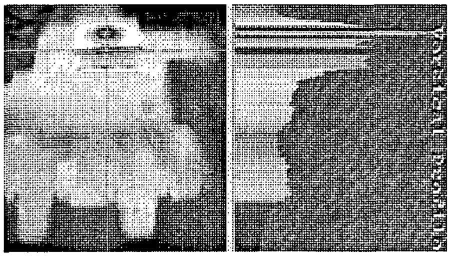


Fig. 12 Thermographic Image of NC board

Though stated many functions are necessary for a successful NC controller, practically its reliability should be assured to the highest level because NC machines are usually installed in harsh environments. In this regard, we are conducting many tests for the evaluation of reliability. One typical example is shown in Fig. 12, which is the thermographic image of the 380Mi NC board to identify hot spots that can lead the NC system to a catastrophic freeze state.

High-speed machine tools consequently require more intelligence in CNC function. In the past, intelligence of a machine was largely focused to simple, local monitoring function such as operating condition and tool monitoring. Today's more stringent requirements for machining intensify the importance of intelligence in machining. Such intelligence function includes: look-ahead control that reads many blocks of NC codes in advance; acceleration/deceleration before interpolation that enables the highest figure accuracy possible even at high feed speeds; automatic feed speed control that changes cutting feed according to the shape of workpieces with little user intervention; thermal-error compensation that corrects machine deviations resulted from temperature rises; cutting force control that changes feed or spindle speed according to variations of cutting force for fast machining.

As stated before, manufacturing system becomes wired so that a machine can be accessed remotely. With the help from this sort of infrastructure, remote maintenance becomes one fast growing subject in service intelligence. By integrating with local maintenance function such as shown in Fig. 13, we can provide a wide range of additional services apart from simple passive maintenance.

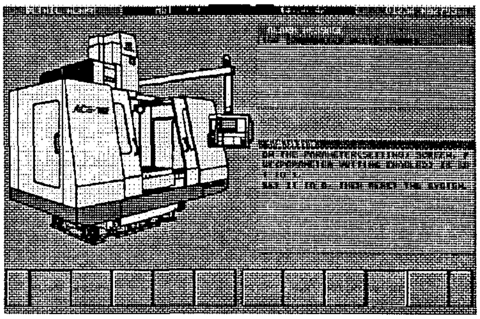


Fig. 13 NC Screen showing Local Maintenance

4. Conclusions

This paper firstly emphasized high-speed spindle technology as a basis for next-generation machine tools, and then issues regarding feed axes were addressed. Finally we took a look at what happens when each mechanical element is assembled to a system that meets with a NC controller. From the past to the future, the main technical issues in machine tools must be their accuracy and productivity, which were the mainstream topics in this paper. In this regard, next-generation machine tools do not stand far away from the tradition form, but fairly great strides should be made to meet today's tough stringent machining requirements and to result in not highly-priced, well-optimized machines for the next generation manufacturing industry.

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