CONSIDERATION OF ACCURACY FOR NUMERICALLY CONTROLLED MACHINE TOOLS*

By

M. SOEDA

Department of Machine Operation, Faculty of Engineering, Tokai University

Received October 22, 1978

Introduction

One of the most outstanding merits of numerically controlled machine tools is to be far superior in accuracy to conventional machine tools, as our survey demonstrates it.

Accuracy depends mostly on lost motions such as friction, backlash, distortion in connection with stiffness and resonance frequency etc.

As a whole, the indirect feedback system is hardly affected by lost motions or resonance frequency, so long as accuracy is not affected seriously. Accordingly, it is obviously helpful to get a stable control.

On the contrary, the direct feedback system is affected sensitively by characteristics of machine elements, especially in relation to the lost motion.

In case of massive or gigantic machine tools which are to be controlled at a high speed, it is very difficult to get fine control and also to predetermine the characteristics in regard to lost motions in details.

In addition to this, it is hard to make the lost motion to keep constantly within certain small values. For this purpose, an improved servo-control system is introduced.

In Japan, numerical control (N/C) systems were introduced about 1950. Nowadays N/C devices have been spread and popularized in many field as numerical machine tools, automatic drafters, automatic welder and gas cutters, robots and so on.

Up to now, nearly about 18,000 of N/C machine tools have been installed not only in big companies but also in small ones, such as ship building, electric machinery, construction machinery and machine tools. The ratio of N/C to conventional machines has been roughly 20% in the a recent year.

Servo-control system demands digital technique, analog technique and special servo-control technique. The system is one of the most important, difficult and delicate works.

* Submitted at the Joint Symposium Technical University Budapest — Tokai University, 23—24 November, 1977.

At the early stage, a lot of troubles happened because of shortage of the special servo-control technique or unknown characteristics of devices. Up to now, these essential factors which have much concern with the accuracy, have been analyzed and studied not only theoretically but also experimentally. For instance, relations between accuracy and system gain are discussed in connection with inertia, friction, backlash, distortion, stick-slip and resonance etc.

In some instances, more precise servo-control systems are essential to obtain accurate and rapid control or to deal with some compliacted devices, especially for the case of big machines. To meet this demand, a certain method is introduced by the end of this paper.

Comparison of accuracy errors

Examples of the measuring data on some pieces machined by conventional machine and *N/C* machine are shown in Table 1 and 2 respectively.

Consideration of accuracy

If accuracy of numerical control machine tools is discussed, the following items should mainly be taken into consideration, although measuring values follow the nature of statistical normal distribution.

Table 1

Measuring data of actual samples machined by a conventional machine

Parts No.	Size	Parts No.	Size	Parts No.	Size	Parts No.	Size
1	40.012	12	39.982	23	40.025	34	39.961
2	39.968	13	40.019	24	39.951	35	39.978
3	39.976	14	39.976	25	39.963	36	39.975
4	39.951	15	39.966	26	40.008	37	39.966
5	39.955	16	39.977	27	39.986	38	40.021
6	39.977	17	39.974	28	39.967	39	39.989
7	39.993	18	39.019	29	39.975	40	39.979
8	39.953	19	40.011	30	39.978	41	39.967
9	39.969	20	39.979	31	40.015	42	39.989
10	40.025	21	39.979	32	40.029		
11	39.958	22	39.978	33	39.986		

Table 2

Measuring data of actual samples machined by a N/C

Parts No.	Size	Parts No.	Size	Parts No.	Size	Parts No.	Size
1	199.881	9	199.885	17	199.881	25	199.881
2	.881	10	.885	18	.881	26	.881
3	.881	11	.885	19	.881	27	.882
4	.884	12	.881	20	.882	28	.885
5	.898	13	.881	21	.880	29	.881
6	.895	14	.879	22	.881	30	.881
7	.881	15	.882	23	.881	31	.881
8	.885	16	.881	24	.881		

1. Specific characters of the motion of the moving element of machine (exclusive measuring error).
2. Measuring devices and measuring error.

Main items to be considered

(A) *Accuracy of positioning*

Intrinsic characteristics of machine elements, such as static and kinetic frictions, rigidity, and stiffness etc.

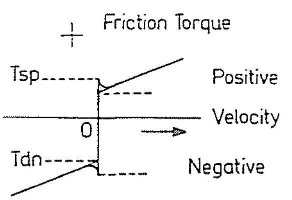

Fig. 1. An approximation on friction

(B) *Repeated accuracy of positioning*

Fluctuation of friction, stiffness of machine, servo stiffness, output power, and fluctuation of input power

(C) *Lost motion*

In general, accuracy can be represented theoreticaly as follows in relation to the lost motion such as friction, backlash, pitch error of driving ball screw, windup and deflection etc.

Lost motion

Positive

$$Lp = \left\{ \frac{T_{sp} + T_{Mp} + T_{DN}}{T_0} \pm \right.$$

$$\left. \pm \sqrt{\left(\frac{\Delta T_{sp}}{T}\right)^2 + \left(\frac{\Delta T_{MP}}{T_0}\right)^2 + \left(\frac{\Delta T_{DN}}{T_0}\right)^2 + (\Delta D_L)^2 + (\Delta C)^2} + 2\,D_L \right\} \times \theta_0$$

Negative (1)

$$Lp = \left\{ \frac{T_{SN} + T_{MN} + T_{Dp}}{T_0} \pm \right.$$

$$\left. \pm \sqrt{\left(\frac{\Delta T_{sN}}{T_0}\right)^2 + \left(\frac{\Delta T_{MN}}{T_0}\right)^2 + \left(\frac{\Delta T_{Dp}}{T_0}\right)^2 + (\Delta D_L)^2 + (\Delta C)^2} + 2D_L \right\} \times \theta_0$$

Accuracy of positioning

Positive

$$n > \frac{T_{sp} \pm \Delta T_{sp} + T_{Mp} \pm \Delta T_{Mp} + T_{DN} \pm T_{DN}}{T_0}$$

$$Ep = \left[\frac{T_{Dp} + T_{DN}}{T_0} \pm \left\{ \left| \sqrt{\left(\frac{\Delta T_{Dp}}{T_0}\right)^2 + \left(\frac{\Delta T_{DN}}{T_0}\right)^2 + (\Delta C)^2 + (\Delta D_E)^2} \right| + D_E \right\} \right] \theta_0$$

Negative (2)

$$n > \frac{T_{sN} - \Delta T_{sN} + T_{MN} \pm \Delta T_{MN} + T_{Dp} \pm \Delta T_{Dp}}{T_0}$$

$$E_N = E_p$$

Repeating accuracy of positioning

$$n > \frac{T_{sp} \pm \Delta T_{sp} + T_{Mp} \pm \Delta T_{Mp} + T_{DM} \pm \Delta T_{DN}}{T_0}$$

$$n > \frac{T_{sN} \pm \Delta T_{sN} + T_{MN} \pm \Delta T_{MN} + T_{Dp} \pm \Delta T_{Dp}}{T_0} \qquad (3)$$

$$\Delta \varepsilon = \pm \sqrt{\left(\frac{\Delta T_{DP}}{T_0}\right)^2 + \left(\frac{\Delta T_{DN}}{T_0}\right)^2 + (\Delta C)^2 + (\Delta D_{\Delta\varepsilon})^2}$$

where

T_{SP}:	average value of static friction in positive direction	[kg-cm]
T_{SN}:	average value of static friction in negative direction	[kg-cm]
T_{DP}:	minimum value of kinetic friction in positive direction	[kg-cm]
T_{DN}:	minimum value of kinetic friction in negative friction	[kg-cm]
Δ:	symbol of fluctuations	[kg-cm]
T_0:	servo motor torque for a unit signal	[kg-cm]
θ_0:	revolution angle of servo motor for a unit signal	[deg.]
T_{MP}:	average value of static friction of servo motor in positive direction	[kg-cm]
T_{MN}:	average value of static friction of servo motor in negative direction	[kg-cm]
Δ:	symbol of fluctuation	
D:	sensing accuracy of transducer	[pulse]
ΔC:	variation of input command, in pulse	[pulse]
D_L:	Backlash	

In a case where two measured values A and B are superposed, having errors A and B respectively, the resultant value can be represented as follow.

$$A + \Delta A \quad B + \Delta B \qquad L = A + B \pm \sqrt{\Delta A^2 + \Delta B^2} \quad \ldots\ldots \quad (4)$$

$|\longleftarrow \quad L \quad \longrightarrow|$

An example of design regarding consideration of error in positioning

Let be

Static friction torque .... ($T_{SP} = T_{SN}$) 30 kg-cm
Fluctuation of torque .... ($\Delta T_{SP} = \Delta T_{SN}$) $\pm$ 3 kg-cm
Minimum kinetic friction torque ..... ($T_{DP} = T_{DN}$) 1.5 kg-cm
Fluctuation of the above value ...... ($\Delta T_{DP} = \Delta T_{DN}$) $\pm$ 1.5 kg-cm
Let maximum kinetic friction be 32.5 kg-cm at the travelling speed 4800 mm/min
Cutting torque maximum 10 kg-cm (including kinetic friction torque)
$GD^2 = 50$ kg-cm^2 at the maximum load.
Cutting speed .... 1200 mm/min
Unit pulse .... 0.01 mm
Revolution of motor shaft .... 2.4°/pulse
Let machine stiffness be .... 1X10 kg-cm

A certain type of motor (e.g. FKR-50) is chosen, and according to another paper,. . .$T_0 = 50$ kg-cm (at 2.4°/pulse)
Values calculated on the motor shaft side.

$$T_0 > T_{SP} + \Delta T_{SP} + T_{MP} + \Delta T_{MP} + T_{DN} + \Delta T_{DN} = 50.7 \text{ Kg-cm}, \quad (5)$$

Eq. (5) must exist in order to let the machine be moved at least by a unit pulse.

Lost motion

$$L_P = L_N = \frac{30 + 15 + 109}{50} \pm \sqrt{(0.06)^2 + (0.001)^2 (0.03)^2 + (0.05)^2} + 0.25$$

$$= (0.92 \pm 0.08 + 0.25) = \underline{(1.17 \pm 0.08) \times 10 \mu m} \quad (6)$$

Accuracy of positioning

$$E_P = E_N = \frac{15 + 15}{50} \pm \{ | \sqrt{(0.03)^2 + (0.03)^2 + (0.05)^2} \, | + D_E \}$$

$$= \underline{(0.6 \pm 0.315) \times 10\mu} \quad (7)$$

Repeating positioning error, in case of $n > 2$ pulses

$$\Delta\varepsilon = \pm\sqrt{(0.03)^2 + (0.03)^2} = \pm 0.042 \times 10\mu = \underline{\pm 0.42 \ \mu m} \quad (8)$$

Considerations regarding the error due to the variation of output power of N/C, variation of power line voltage, and variation of environmental temperature will not be discussed here.

(D) *Dividing accuracy of resolver*

Here one more type of error ε is considered briefly in the case where a resolver is used for sensing. This error is called "Dividing accuracy of resolver". The error usually varies with rotating position as below.

Cause 1: Distortion of sine wave of exciting voltage

Cause 2: Fluctuation of supply voltage of inductor or resolver.

Cause 3: Inherent irregularity of mechanism

$DE =$ Variation of dividing accuracy of resolver caused by position: θ: in case of positioning.

$\varepsilon =$ Variation of dividing accuracy of resolver caused by position θ: in case of positioning repeated.

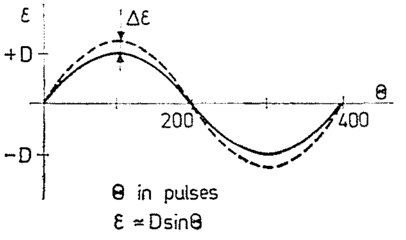

Fig. 2. Variation of error in position

An example of probability of positioning

As the probability of positioning in θ is considered to be equal at any position, the probability of every position can be presumed at 1/400. This means the value of ε (error) varies with its position.

For example, statistically speaking, less than 68.3% (1σ : one sigma) of positioning error out of maximum error D falls within a certain value of position θ determined by the equation below.

$$\varepsilon = D \sin \theta = D \sin (n/400) \times 360$$

$$1\sigma = (D \sin \theta)/D = \sin (360/400) \times n = \sin (0.9\, n)$$

$$\theta = 0.9n \simeq 43^\circ$$

That is,

$$n = 48 \text{ pulses}$$

For $D = 1$, $n = 100$; $48/100 = 0.48$ (probability)

The value 48% indicates that the magnitude of error ε, about 68% of maximum error D, will happen 48 times in positioning.

Comparison of the accuracy of machining by a conventional machine and a N/C machine

Table 3

Machined by a conventional machine tool

	Range (mm)	X (mm)	Frenquency	f	
1	39.950 ~ 39.956	39.953	////	4	Standard
2	39.956 ~ 39.962	39.959	//	2	deviation
3	39.962 ~ 39.968	39.965	///// /	6	S in nearly
4	39.968 ~ 39.974	39.971	//	2	
5	39.974 ~ 39.980	39.977	///// ///// //	12	$S = 0.61$
6	39.980 ~ 39.986	39.983	///	3	
7	39.986 ~ 39.992	39.989	//	2	
8	39.992 ~ 39.998	39.995	/	1	
9	39.998 ~ 40.001	40.001		0	
10	40.004 ~ 40.010	40.007	/	1	
11	40.010 ~ 40.016	40.013	//	2	
12	40.016 ~ 40.022	40.019	////	4	
13	40.022 ~ 40.028	40.025	//	2	
14	40.028 ~ 40.034	40.031	/	1	

Table 4

Machined by a N/C machine tool

	Range (mm)	X (mm)	Frequency	f	
1	$199.877 \sim 199.879$	199.878	/	1	Standard
2	$199.879 \sim 199.881$	199.880	///// ///// ///// /////	19	deviation S
3	$199.881 \sim 199.883$	199.882	///	3	$S = 0.008$
4	$199.883 \sim 199.885$	199.884	///// /	6	
5	$199.885 \sim 199.887$	199.886		0	
6	$199.887 \sim 199.889$	199.888		0	
7	$199.889 \sim 199.891$	199.890		0	
8	$199.891 \sim 199.893$	199.892		0	
9	$199.893 \sim 199.895$	199.894	//	1	
10	$199.895 \sim 199.897$	199.896		0	
11	$199.897 \sim 199.899$	199.898	/	1	

Similarly, 2σ, $\varepsilon = 0.954\ D$

$2\sigma = 0.954 = \sin\theta$ $\qquad n = 81$......about 81%

Similarly, $3\sigma : \varepsilon = 0.997\ D$ $\qquad n = 96$......about 96%

These calculations have been tried just as have been theoretical cases.

Dual Feedback System (D.F.B.S.)

Since semi-closed (indirect feedback) systems are hardly influenced by backlash or natural frequency, it is obviously helpful to get a stable control.

However, a certain magnitude of error will occur as far as the motion of moving element is observed.

The above effect becomes remarkable in case of gigantic machine tools. On the contrary, a direct feedback system (so-called-closed system) is affected sensibly by characteristics of machine elements.

In case of designing a massive machine tool, it is very difficult to estimate features such as backlash, pitch error of ball screw etc. and to obtain an inexpensive high rigidity. Moreover, it is also difficult to keep such a value constant, within a certain small value.

In some cases, these values such as backlash or friction are likely to be affected by the location where the machine is installed.

For this reason, an improved servo-control system for numerical control has been developed (Fig. 3).

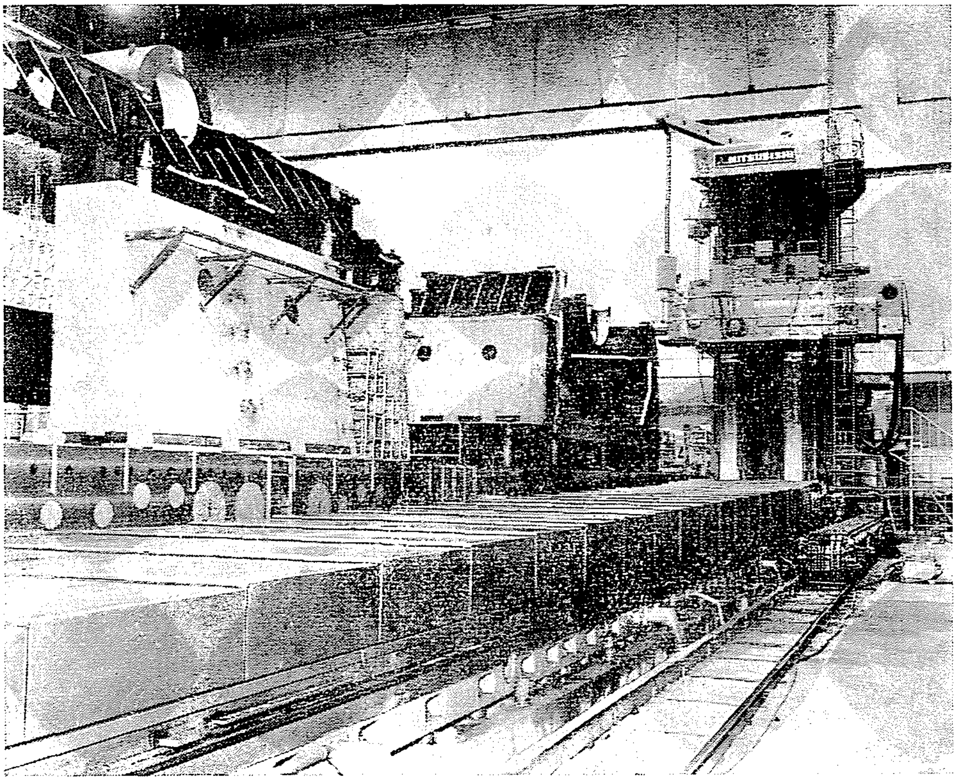

Fig. 3. An example of the biggest machine tools controlled by *N/C* (By the courtesy of Mitsubishi Heavy Industries Limited)

Let me briefly outline this system.

The principle of D.F.B.S.*

In Fig. 4 dotted line represents the direct feedback system alone. Therefore, two outputs Qi and Qo and are compared by the phase detector (1), then error signal Qe comes out, and this error signal is amplified and then the motor is driven so that Qi is equal to Qo: $(Qe \rightarrow 0)$
where

Qi = output signal of digital phase moderator

Qo = output signal of inductosyn

In case of D.F.B.S., a semi-closed loop (indirect feedback) system is contained in the D.F.B.S. as a surplus loop. Therefore, the other two outputs Qi and Qf are also compared, and the error signal Qe permits the motor to drive to as to have $Qi = Qf$.

* This system has been developed by Mitsubishi Electric Corp. with the co-operation of the author.

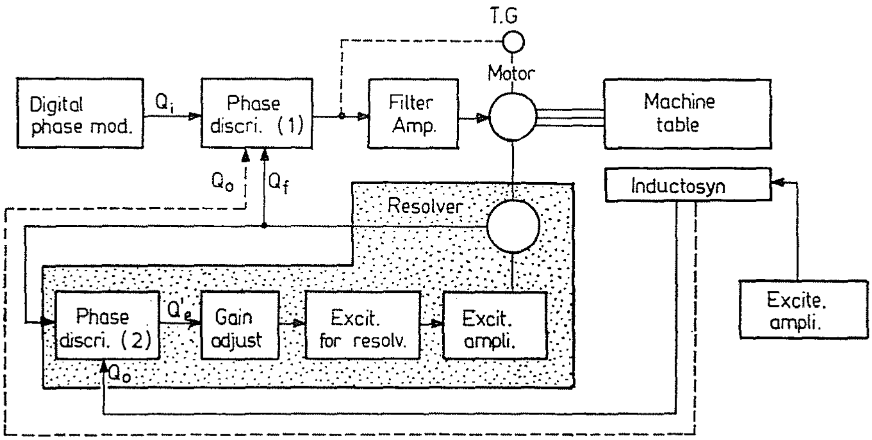

Fig. 4. Dual feedback systems

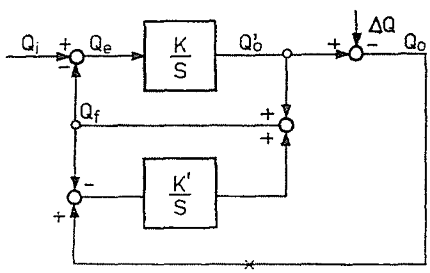

Fig. 5. Block diagram of D.F.B.S
ΔQ: mechanical error

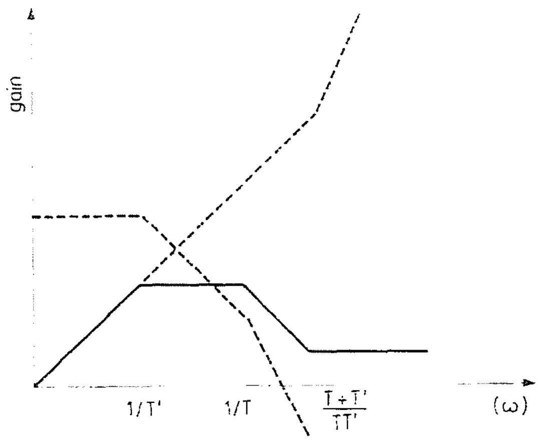

Fig. 6. Bode diagrams of DFBS

In the case where the exciting signal of resolver is quite the same as that of inductosyn, the D.F.B.S. system will be considered only as a semi-closed loop system.

In the D.F.B.S., however, the phase of exciting signal of resolver is controlled by the output of inductosyn.

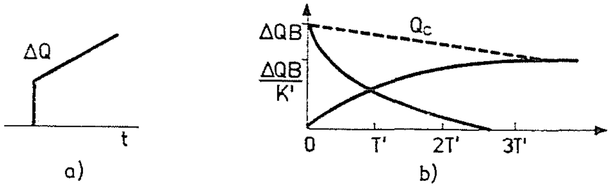

Fig. 7. Errors vary with time

That is:

Qf and Qo are compared by the phase detector (2), Qe (error phase) is given to the exciting circuit of resolver in order to dephase the exciting current of the resolver, namely, the difference between Qo and Qi is feedback to the resolver.

This allows backlash and pitch error to move into the resolver.

For this reason, it seems that the system which is composed by phase detector, filter amplifier, motor and resolver etc. can be considered as a system which include the moving table of the machine tool.

Consequently the gain of this system can be considered almost without many factors of machine such as backlash, resonance frequency, pitch error and so on.

For this reason, D.F.B.S. has a good stability and nearly the same controllability as semi-closed loop systems.

Appendix

Theory of D.F.B.S.

$$Qi - Qf = Qe \tag{1}$$

$$Qe \times \frac{K}{S} = Q\sigma' \tag{2}$$

$$Q\sigma' - \Delta Q = Q\sigma \tag{3}$$

$$Qo' + (Qo - Qf)\frac{K'}{S} = Qf \tag{4}$$

from Eqs (2), (3):

$$Qe = \frac{S}{K}(Q\sigma + \Delta Q) \tag{5}$$

from (1), (5):

$$Qf = Qi - \frac{S}{K}(Q\sigma + \Delta Q) \tag{6}$$

from (3), (4):

$$Q\sigma + \Delta Q + (Q\sigma - Qf)\frac{K'}{S} = Qf \tag{7}$$

$$\therefore Q\sigma\left(1+\frac{K'}{S}\right) + \Delta Q = Qf\left(1+\frac{K'}{S}\right)$$

from (7), (6):

$$\left(1+\frac{S}{K}\right)Q\sigma \div \left(\frac{1}{1+\frac{K'}{S}} + \frac{S}{K}\right)\Delta Q = Qi \tag{8}$$

$$Q\sigma = \frac{1}{1+\frac{S}{K}}Qi - \frac{1}{1+\frac{S}{K}}\left(\frac{1}{1+\frac{K'}{S}} + \frac{S}{K}\right)\Delta Q\,. \tag{9}$$

Let $Qi = \theta$

$$Q\sigma = -\frac{1}{1+\frac{S}{K}}\left(\frac{1}{1+\frac{K'}{S}} + \frac{S}{K}\right)\Delta Q = \frac{1}{1+\frac{S}{K}}\left\{\frac{S(S+K+K')}{K'(S+K')}\right\}\Delta Q$$

$$\lim_{t\to\infty}\frac{Q\sigma}{\Delta Q} = \lim_{z\to 0}\frac{Q\sigma}{\Delta Q} = \lim_{z\to 0}\frac{1}{1+\frac{S}{K}}\left\{\frac{S}{K}\,\frac{(S+K+K')}{(S+K')}\right\} \to 0$$

Let $\Delta Q = \theta$

$$Q\sigma = \frac{1}{1+\frac{S}{K}}Qi$$

$$\lim_{t\to\infty}\frac{Q\sigma}{Qi} = \lim_{z\to 0}\frac{Q\sigma}{Qi} = \lim_{z\to 0}\frac{1}{1+\frac{S}{K}} \to 1$$

trying to analyse the response

where $\frac{1}{K} = T$; $\frac{1}{K'} = T'$

From (9)

$$Q\sigma(S) = \frac{1}{1+TS}Qi(S) - \frac{1}{1+TS}\left(\frac{T'S}{1+T'S} + TS\right)\Delta Q(S)$$

$$= \frac{1}{1+TS}Qi(S) + \left(\frac{1}{(1+TS)(1+T'S)} - 1\right)\Delta Q(S) \tag{10}$$

where $\varDelta Q(S)$ is given as a step input, let be $T \neq T'$ and $Qi\,(s) = 0$

$$Q(s) = \frac{1}{S}\left(\frac{1}{(1+TS)\,(1+T'S)} - 1\right)\varDelta Q(S)$$

$$= \left\{\frac{1}{S} - \frac{T^2}{(T-T')}\frac{1}{(1+TS)} + \frac{(T)'^2}{T-T}\frac{1}{(1+T'S)} - \frac{1}{S}\right\}\varDelta Q(S)$$

$$= \frac{1}{(T-T')}\left((T')^2\frac{1}{1+T'S} - (T)^2\frac{1}{(1+TS)}\right)\varDelta Q(S)$$

$$\therefore Q\sigma = \frac{1}{T'-T}\left(T\,e^{-\frac{t}{T}} - T'e^{-\frac{t}{T'}}\right)\varDelta Q(S) \tag{11}$$

Let $T' = \alpha T$

$$Q\sigma = \frac{1}{T}\frac{1}{(\alpha-1)}\cdot T\left(e^{-\frac{t}{T}} - \alpha e^{-\frac{t}{\alpha T}}\right)\varDelta Q(S)$$

$$= \frac{1}{\alpha - 1}\cdot\left(e^{-\frac{t}{T}} - \alpha e^{-\frac{t}{\alpha T}}\right)\varDelta Q(S)$$

$$= \frac{1}{\alpha - 1}\cdot e^{-\frac{t}{T}}\left(1 - \alpha e^{-\frac{t}{\alpha T}(1+\alpha)}\right)\varDelta Q(S) \tag{12}$$

Values of Q in regard to α are shown in the figure. If $\varDelta Q_s$ is represented in a Bode diagram, then $G(S) = \dfrac{Q\sigma(S)}{\varDelta Q(S)}$ is as follows:

$$G(S) = \frac{1}{(1+TS)\,(1+T'S)} - 1$$

$$= \frac{-S(T+T'+TT'S)}{(1+TS)\,(1+T'S)} = \frac{(T+T')\,S\left(1+\dfrac{TT'}{T+T}S\right)}{(1+TS)\,(1+T'S)} \tag{13}$$

Frequencies at break points are shown below.

$$\frac{T+T'}{TT'} - \frac{1}{T'} = \frac{1}{T}$$

$$\frac{T+T'}{TT'} - \frac{1}{T} = \frac{1}{T'}$$

Even in a case where $\varDelta Q$ is supposed to be the resonance vibration, it will do good as far as the resonance frequency is greater than $\dfrac{T+T'}{TT'}$
For example, let $T' = \alpha T$

$$G(S) = \frac{T(1+\alpha)\,S \times \left(1+\dfrac{T}{1+\alpha}S\right)}{(1+TS)\,(1+\alpha TS)} \tag{14}$$

$$| G(S) | = 20 \log T(1+\alpha)\,\omega + 20 \log \frac{T}{1+\alpha}\,\omega - 20 \log T\omega - 20 \log \alpha T\omega$$

where

$$\omega = \frac{T+T'}{TT'} = \frac{1+\alpha}{\alpha T}$$

$$| G(S) |_{\frac{1+\alpha}{\alpha T}} = 20 \log \frac{(1+\alpha)^2}{\alpha} + 20 \log \frac{I}{\alpha} - 20 \log \left(\frac{1+\alpha}{\alpha}\right) -$$

$$- 20 \log (1+\alpha) = 20 \log \frac{1}{\alpha}\,[\mathrm{d}B]\,.$$

If $\alpha < 1$, then $| G(s) | > 1$, therefore it is an impossibility to use. For instance, let us examine the relationship between $Q\sigma - Q_f$ and ΔQ.

$$Q\sigma - Qf = \frac{-S}{S+K'}\,\Delta Q = Qc$$

The response of Qc responding to step input of ΔQ is, in the case where the magnitude of step input is ΔQ_B:

$$Qc = -e^{-K't}\,\Delta Q_B = -e^{-\frac{t}{T'}}\,\Delta Q_B\,.$$

Similarity exists in case where ΔQ is a lamp input.

Here, let ΔQ_P be an error per second.

$$Qc = -\frac{1}{K'}(1 - e^{-K't})\,Q_P = -\frac{1}{K'}\left(1 - e^{-\frac{t}{T'}}\right) \cdot \Delta Q_P \tag{15}$$

For the case where backlash and pitch error occur at the same time, the result of Qc is shown as a dotted line.

$$Qc = -\left[e^{-\frac{t}{T'}}\,\Delta Q_B + \frac{1}{K}\left(1 + e^{-\frac{t}{T'}}\right)\Delta Q_P\right]$$

$$= -e^{-\frac{t}{T'}}(\Delta Q_B - T'\,\Delta Q_P) - T'\,\Delta Q_P\,. \tag{16}$$

Let $T' = 1 = K'$

$$= -\,e^{-t}(\Delta Q_B - \Delta Q_P) - \Delta Q_P = -\,\Delta Q_P + e^{-t}(\Delta Q_P - \Delta Q_B)$$

For, $\Delta Q_P > \Delta Q_B$, if $\Delta Q_P - \Delta Q_B - 3$, then

$$Qc = -\Delta Q_P + e^{-t}\,\delta \leqq -\Delta Q_P\,.$$

For, $\Delta Q_P < \Delta Q_B$ if $\Delta Q_B - \Delta Q_P = \gamma$, then

$$= -\Delta Q_P - e^{-t}\,\gamma = -\Delta Q_B + \delta(1 + e^{-t}) \leqq \Delta Q_B$$

In any case, Qc does not exceed either ΔQ_P or ΔQ_B.

Summary

As the comparison of the accuracy between a N/C machine tool and a conventional one shows, a N/C machine tool is far superior to a conventional one in regard to machining accuracy. However, positioning accuracy depends naturally on many kinds of lost motions such as friction, backlash, windup and so on. Some calculations are tentatively tried in relation to accuracy.

In a case where a very large-scale machine tool is designed or has to be controlled rapidly, it is somewhat troublesome to get fine accuracy. To meet this demand, a certain control system: so-called "dual feedback system" is introduced.

Prof. Minoru SOEDA, Dept. of Machine Operation, Faculty of Eng. Tokai University, 1117 Kitakaname Hiratsuka-Shi Kavagawa Japan.