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RECENT CONTROL SYSTEMS FOR VARIABLE-SPEED DRIVE

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1. FOREWORD

There are increasing requirements for more quality, reliability, efficienty and labor saving in various field of variable-speed drive unit application. On the other hand, with progress of microelectronics, use of digital control systems including those applicable to the variable-speed drive unit has become popular; those digital systems bringing increased freedom of software and facilitated information processing. Under the circumstances, FUJI ELECTRIC is making efforts to make the best use of advantages of digital control through the introduction of the modern control theory and other advanced control systems as well as the expansion of the supervisory control functions. This paper relates mainly to the technical trend of those recent control systems for variable-speed drive.

2. ADVANCED CONTROL SYSTEMS

With increasing needs for the advanced digital systems for variable-speed control, there are studies of establishing the control systems based on the digital control theory, which take in place of an approximation of continuous-time system, and improving the quality of control by the application of modern control theory. The following are typical of those advanced control system.

2.1 Digital observer

The principle of the observer (state observing apparatus), with which the state of controlled object can be estimated from its input and output, is expressed by equations (1) and (2):

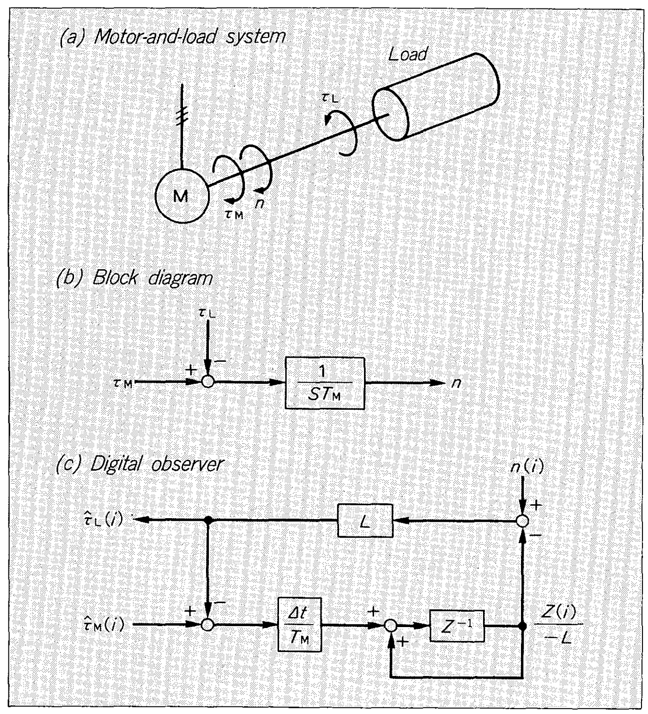
$$z(i+1) = \hat{A}z(i) + \hat{B}y(i) + \hat{J}u(i) \quad (1)$$

$$\hat{x}(i) = \hat{D}y(i) + \hat{C}z(i) \quad (2)$$

Where, z, y, u and x represent observer's state variable vector, output vector, input vector, and controlled object's state variable vector, respectively; and $\hat{A}$, $\hat{B}$, $\hat{J}$, $\hat{D}$, $\hat{C}$ represent parameter matrix.

With regard to the motor-and-load system shown in *Fig. 1 (a)* and *(b)*, state equation (3) and output equation

Fig. 1 Digital observer



(4) for the discrete time system in sampling period Δt are:

$$x(i+1) = \begin{pmatrix} 1 & -\dfrac{\Delta t}{T_M} \\ 0 & 1 \end{pmatrix} x(i) + \begin{pmatrix} \dfrac{\Delta t}{T_M} \\ 0 \end{pmatrix} u(i) \quad (3)$$

$$y(i) = [1 \;\; 0]\, x(i) \quad (4)$$

While, state variable vector $x(i)$ and input vector $u(i)$ are formularized, respectively, as follows:

$$x(i) = \begin{pmatrix} n(i) \\ \tau_L(i) \end{pmatrix}, \; u(i) = \tau_M(i) \quad (5)$$

Where, T_M, n, τ_M, τ_L represent time constant, speed and torque of the motor as well as load torque, respectively.

By applying the observer equations (1) and (2) to the motor model equations (3) through (5), the minimal order observer expressed by equations (6) and (7) can be drawn. And its structure is shown in *Fig. 1 (c)*.

$$z(i+1) = (1+\frac{\Delta t}{T_M} L) z(i) + \frac{\Delta t}{T_M} L^2 n(i) - \frac{\Delta t}{T_M} L \tau_M(i) \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

$$\begin{pmatrix} n(i) \\ \hat{\tau}_L(i) \end{pmatrix} = \begin{pmatrix} 1 \\ L \end{pmatrix} n(i) + \begin{pmatrix} 0 \\ 1 \end{pmatrix} z(i) \quad \ldots\ldots (7)$$

Where, $\hat{\tau}_L(i)$: Estimated load torque
L: Observer gain

2.2 Digital filter

Such a filter as shown in *Fig. 2 (a)* is expressed by differential equation (8):

$$\dot{x} = -\frac{1}{T} x + \frac{1}{T} u \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

By transforming this into the discrete time system in sampling period Δt, equation (9) is drawn.

$$x(i+1) = e^{-\frac{\Delta t}{T}} x(i) + (1 - e^{-\frac{\Delta t}{T}}) u(i) \quad \ldots\ldots (9)$$

Hereupon, the equation (9) can be rearranged to equation (11) by substituting equation (10) into it.

$$\Phi(z) = 1 - e^{-\frac{\Delta t}{T}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

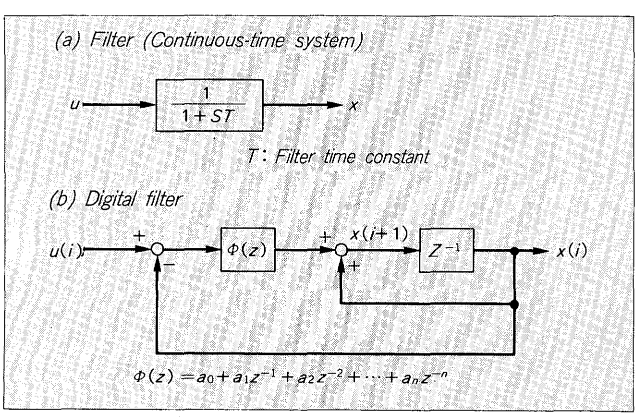
$$x(i+1) = x(i) + \Phi(z) \quad u(i) - x(i) \quad \ldots\ldots (11)$$

This equation represents a recursive filter. For further improvement of performance, a digital filter such as shown in *Fig. 2 (b)* can be formed by incorporating the non-recursive running average filter represented by equation (12) into $\Phi(z)$ in equation (11).

$$\Phi(z) = a_0 + a_1 z^{-1} + a_2 z^{-2} + \ldots\ldots + a_n z^{-n} \quad \ldots (12)$$

Where, a_0, a_1, a_2, ... a_n represent constant and z represents delay element.

Fig. 2 Digital filter



2.3 LQI control

The following is the principle of the LQI control (integral type optimal regulator) which is intended for the purpose of minimizing the linear quadratic performance function and furthermore uses integral control to eliminate offset.

Supposing the state equation of controlled object as equation (13) and the output equation as equation (14),

$$\boldsymbol{x}(i+1) = \boldsymbol{A}\boldsymbol{x}(i) + \boldsymbol{B}\boldsymbol{u}(i) \quad \ldots\ldots\ldots\ldots\ldots (13)$$

$$\boldsymbol{y}(i) = \boldsymbol{C}\boldsymbol{x}(i) \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Where, $\boldsymbol{x}$, $\boldsymbol{u}$, $\boldsymbol{y}$ represent state variable vector, input vector, and output vector, respectively; and $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ represent parameter matrix. Now, let us define the error of output "$\boldsymbol{y}$" from its desired value as,

$$\boldsymbol{v}(i+1) = \boldsymbol{y}(i) - \boldsymbol{r}(i) \quad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

Expanding the equations (13) and (14) to the system which relates to the variations (16) from equilibrium points $\boldsymbol{x}_0$, $\boldsymbol{u}_0$, $\boldsymbol{v}_0$, and $\boldsymbol{y}_0$ $(=\boldsymbol{r})$ results in equations (17) and (18).

$$\Delta\boldsymbol{x} = \boldsymbol{x} - \boldsymbol{x}_0, \Delta\boldsymbol{u} = \boldsymbol{u} - \boldsymbol{u}_0, \Delta\boldsymbol{v} = \boldsymbol{v} - \boldsymbol{v}_0,$$

$$\Delta\boldsymbol{y} = \boldsymbol{y} - \boldsymbol{y}_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

$$\Delta\overline{\boldsymbol{x}(i+1)} = \overline{\boldsymbol{A}}\Delta\overline{\boldsymbol{x}(i)} + \overline{\boldsymbol{B}}\Delta\overline{\boldsymbol{u}(i)} \quad \ldots\ldots\ldots (17)$$

$$\Delta\boldsymbol{y}(i) = \overline{\boldsymbol{C}}\Delta\overline{\boldsymbol{x}(i)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

Where,

$$\Delta\overline{\boldsymbol{x}(i)} = \begin{pmatrix} \Delta\boldsymbol{x}(i) \\ \Delta\boldsymbol{v}(i) \end{pmatrix}, \overline{\boldsymbol{A}} = \begin{pmatrix} \boldsymbol{A} & 0 \\ \boldsymbol{C} & 0 \end{pmatrix}, \overline{\boldsymbol{B}} = \begin{pmatrix} \boldsymbol{B} \\ 0 \end{pmatrix},$$

$$\overline{\boldsymbol{C}} = [\boldsymbol{C} \ 0]$$

Supposing $\boldsymbol{Q}$ and $\boldsymbol{R}$ as weighting matrix, performance function $\boldsymbol{J}$ is expressed by equation (19):

$$\boldsymbol{J} = \sum_{i=0}^{\infty} \{\Delta\overline{\boldsymbol{x}(i+1)}^T \boldsymbol{Q}\Delta\boldsymbol{x}(i+1) + + \Delta\overline{\boldsymbol{u}(i)}^T \boldsymbol{R}\Delta\boldsymbol{u}(i)\} \quad \ldots\ldots\ldots (19)$$

The first term of the right side of equation evaluates the variation of state. The second term evaluates the variation of input or, in other words, the variation of energy. State feedback necessary for minimizing "$\boldsymbol{J}$" is expressed by equation (20):

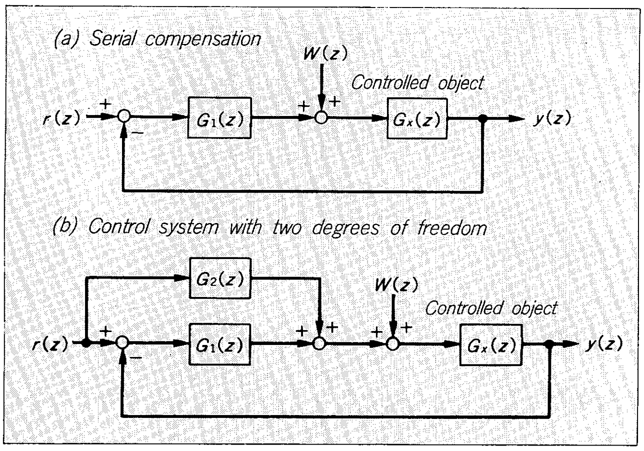
$$\Delta\boldsymbol{u}(i) = -\boldsymbol{F}\Delta\boldsymbol{x}(i) - \boldsymbol{K}\Delta\boldsymbol{v}(i) \quad \ldots\ldots\ldots\ldots (20)$$

The feedback coefficients $\boldsymbol{F}$ and $\boldsymbol{K}$ can be derived from Riccati's equation.

2.4 PID control with two degrees of freedom

In a control system such as shown in *Fig. 3 (a)*, transfer function $H_r(z)$ from target value $r(z)$ to controlled value $y(z)$ is expressed by equation (21); and transfer function $H_w(z)$ from disturbance $w(z)$ to controlled value $y(z)$ is

Fig. 3 Control system with two degrees of freedom



expressed by equation (22):

$$H_r(z) = \frac{G_1(z)G_x(z)}{1+G_1(z)G_x(z)} \quad \ldots\ldots\ldots\ldots\ (21)$$

$$H_w(z) = \frac{G_x(z)}{1+G_1(z)G_x(z)} \quad \ldots\ldots\ldots\ldots\ (22)$$

This involves the possibility that disturbance characteristic and target follow-up characteristic cannot be improved at the same time as the both characteristics are determined solely by $G_1(z)$.

While, in the control system such as shown in *Fig. 3(b)*, transfer functions $H_r(z)$ and $H_w(z)$ are expressed by equations (23) and (24), respectively:

$$H_r(z) = \frac{\{G_1(z)+G_2(z)\}\ G_x(z)}{1+G_1(z)G_x(z)} \quad \ldots\ldots\ (23)$$

$$H_w(z) = \frac{G_x(z)}{1+G_1(z)G_x(z)} \quad \ldots\ldots\ldots\ldots\ (24)$$

In this case, it is possible to improve the target follow-up characteristic by means of $G_2(z)$ in the equation (23) even after the value of $G_1(z)$ has been selected so as to realize quick compensation for disturbance. This is the system called the control system with two degrees of freedom. When applied to an electric motor speed control system, it realizes the PID control with two degrees of freedom in which the PI-control speed regulator corresponds to $G_1(z)$ and the feed forward command corresponds to $G_2(z)$.

2.5 Positioning control using performance function

For positioning control which controls a drive unit with variations of position being followed up so that a stop at the fixed position can be made, it is necessary to eliminate shocks at the deceleration start position and the stop position and also to attain a stop quickly with accuracy. To attain this, it is necessary to give an appropriate speed command so that the variation in deceleration is minimized in the range from the deceleration start position (deceleration at that position is to be set to zero) to the stop position. So, let us suppose a performance function such as formularized in equation (25) which expresses square integral of time differential of deceleration in the range from the deceleration start position to the stop position:

$$J = \int_0^T \dddot{x}^2(t)\,dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (25)$$

Where, T and $x(t)$ represent the time and position, respectively, in the course of deceleration.

By determining the value of $x(t)$ by calculus of variation to minimize "J", the variation in deceleration can be minimized. Supposing speed v_0 and position x_0 at the deceleration start position ($t=0$), the boundary condition is expressed by equation (26):

$$\left.\begin{array}{lll} \text{Position:} & x(0)=x_0, & x(T)=0 \\ \text{Speed:} & \dot{x}(0)=v_0, & \dot{x}(T)=0 \\ \text{Deceleration:} & \ddot{x}(0)=0, & \ddot{x}(T)=0 \end{array}\right\} \quad \ldots\ldots\ (26)$$

The solution of equation (25) is expressed by equation (27), which is in turn converted by time differential into equation (28) which gives speed $v(t)$:

$$x(t) = a_5t^5 + a_4t^4 + a_3t^3 + a_2t^2 + a_1t + a_0 \ \ldots\ (27)$$

Where, $a_0, a_1, a_2, a_3, a_4, a_5$ represent constants.

$$v(t) = 5a_5t^4 + 4a_4t^3 + 3a_3t^2 + 2a_2t + a_1 \ \ldots\ldots\ (28)$$

Therefore, the appropriate position-dependent speed command expressed in equation (29) is derived from equations (27) and (28):

$$v^* = v(x) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (29)$$

By applying that command to the drive unit in question, shocks will be eliminated at both the deceleration start position and the stop position. Accordingly, it will become unnecessary to use any shock absorbing circuit which is attended with a wasteful time lag in the later stage.

3. MONITORING AND DIAGNOSIS OF TROUBLE

3.1 RAS

The concept of "RAS" (Reliability, Availability, and Serviceability) has been popular in the field related to computers. This concept is becoming indispensable also in the field of variable speed control, with development of systematized plants and direct-digital-control (DDC) systems.

The DDC systems for variable speed control application are improved in reliability in various ways. For example "software" supersedes "hardware" in many functions; ASICs (Application Specific ICs) are adopted to realize the highly reliable circuits with reduced number of component parts; and action and signal related to the microcomputer peripheral circuits are tested and monitored when power is ON and during operation to prevent possible failures including runaway of CPU which are peculiar to this kind of systems. In software, additionally, measures such as rerun in case of failure and data rationality cheek, etc. are taken to prevent erroneous detection, and improve reliability in total. Furthermore, detection of important failures (such as overcurrent and overvoltage) are made redundantly through hardware and software to assure highly reliable detection.

In the specific case such as a large-capacity rolling mill, it may involve the possible damage to the whole facility if the mill should be stopped by a failure during rolling operation. A countermeasure, called the "reduction run" is taken to limit the stop of and damage to the facilities to the minimum as far as possible.

As for serviceability, the gain and offset adjustments of analog signal circuit are made through the software method, so that the volume-less and tuning-less circuit realizes a maintenance-free unit. On the loader and personal computer used as service tools, various control parameters can be indicated by the familiarized units such as "%" and "rpm" to make the tools convenient for using for maintenance work.

3.2 Trace back

One of the important items of RAS function is to find out the cause of trouble, in case it occurs, and take the necessary measure in a short time. As the necessary function to facilitate troubleshooting, the trace-back system is available which includes in-sequence trouble recording function, which makes discrimination of a primary failure from the influenced secondary failure, and the various control data tracing back function.

The trace-back system continuously recordes the inside data and controlled variables at the fixed sampling periods during operation of a control system so that the data in a fixed term can be always maintained up to date. If a failure occurs, recording is stopped after a lapse of a fixed time. By tracing back the recorded data, therefore, the state of the control system before and after the trouble becomes clear; this provides the highly dependable way of troubleshooting. The loader allows free selecting of the desired kinds of data to be recorded, sampling periods, range of recording time, and time to a stop of recording after occurence of a failure.

The in-sequence trouble occurence record and trace-back data are stored in a non-volative memory which maintains the contents even when control power is cut out and/or when resetting of faulty circuit. Accordingly, immediate restart of operation is possible even in case of a stop of the facility caused by occurence of a failure, provided that resetting of the faulty circuit is possible, to minimize downtime of the facility. The related information can be displayed on the control-unit side using a transportable service tool such as the loader or personal computer. Furthermore, to meet the requirements for the labor-saving plant and for centeralization of control and monitoring, an adequate method is used in such a way that RAS information from the individual control units is collected through data way and centered on an upper stage of the man-machine monitoring controller (PMS).

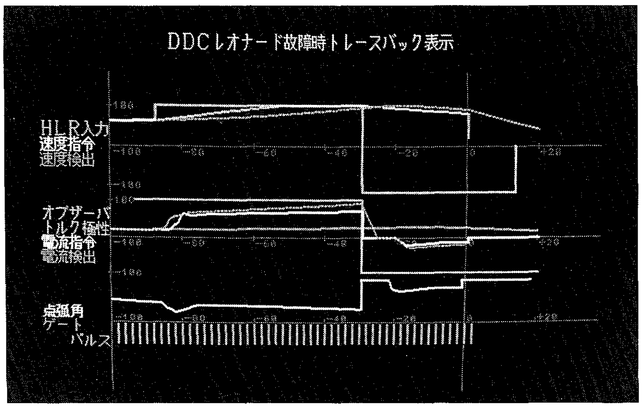


Fig. 4 Example of displayed trace-back data

An example of displayed track-back data is shown in *Fig. 4*.

3.3 AI

The above-mentioned RAS system brings people information necessary for grasping trouble symptoms and finding the causes of trouble. Because of person-dependent function, speedy troubleshooting with accuracy using RAS depends largely upon personal experience and knowhow. To cope with such person-dependent problem, FUJI ELECTRIC is making efforts to develop an expert system which is able to bring the appropriate pieces of advice on the basis of accumulated personal experience and knowhow. Such an expert system will be largely useful for the purposes of labor-saving, downtime reduction, and training of beginners. This expert system uses the expert system constructing tool, call the COMEX (Compact Knowledge based Expert System) which runs on personal computers. Update and addition of knowledge base can be made by anyone who is ignorant in computer language. Expansion to an on-line system is also possible in the future. The system which has now been developed aims at diagnosis of armature and field circuits, thyristor converter, main AC circuits, and control circuits (current, voltage and speed detectors of DC drives) and it brings necessary troubleshooting information such as the fault signal of the control devices, trace-back data, etc. The inference engine will ask the person at the display which to choose and, in the interactive form, the person can choose an input using an YES/NO key or a numeral key in accordance with the aforementioned RAS information. The result will be an output of conclusive hypothesis. If two or more conclusive hypotheses are suspected, each hypothesis will be classified as rank A, B or C depending on the degree of possibility as a cause of trouble. Additionally, it is also possible to display detailed information about the method of investigation and the measures to be taken.

4. TYPICAL APPLICATION TO PLANT

4.1 Function load sharing between programmable controller (PC) and variable speed control unit

As mentioned in section [2], FUJI ELECTRIC has been making efforts to develop the advanced control, particularly about its software based on the digital control theory. Since the digital control theory makes it possible to use computing time effectively, which could not be achieved by an approximation of continuous-time system, the variable speed control unit using the advanced control is improved in performance including the adoption of the observer. As for control function, however, it is limited to below the level of the speed control system so as to promote standardization of the unit. That is, to make the separation of function clear, function peculiar to the plant facilities is processed by PC which features flexible accommodation to requirements, while the variable speed control unit acting as a simple drive unit which operates under speed-commands (or torque-commands) from PC.

4.2 Impact drop suppression torsional vibration suppression, noise elimination

(1) Impact drop suppression

At the moment the rolled material is caught in the rolling mill, load torque of the motor increases stepwise, causing a transient drop of motor speed (called the "impact drop"). This phenomenon will be a principle cause of a deterioration in the quality of products. To cope with this problem, impact drop suppression is made by the feed forward of a current reference, corresponding to the load torque estimated by the observer, to the current control system. The structure of impact drop suppression system is shown in *Fig. 5*.

(2) Torsional vibration suppression
(2) Torsional vibration control

In the speed-control system in which a motor and its load are connected elastically to each other, as shown in *Fig. 6.* (a) and (b), a problem may arise due to occurence of torsional vibrations in existence of step-to-step load disturbances. Conventional methods taken to avoid increase of vibrations were either to increase rigidity of the shaft so as to shift the resonance frequency of the mechanical system toward the high-frequency side or to shift the control system cutoff frequency toward the low-frequency side, at the sacrifice of control performance. Using the LQI control, however, makes it possible to suppress those vibrations electrically, by the feedback of the state of speed and shaft torque of both the motor and its load. The structure of torsional vibration suppression system using LQI control is shown in *Fig. 7*. In this system, the observer is used to estimate speed of load and shaft torque which connot be detected directly.

(3) Noise elimination

In the control systems shown in *Figs. 5* and *7*, output of the digital observer will be affected largely by noises such as ripples included in detected speed and current signals. Those undesirable noises can be removed from signals by the use of the highly effective digital filters aforementioned in section 2.2; and the digital observer can bring its function into fully play.

Fig. 5 Impact drop control by digital observer

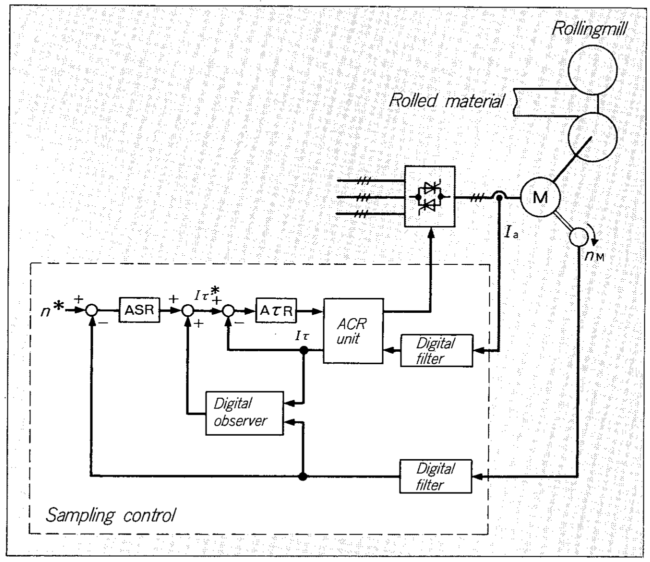


Fig. 6 Motor-shaft-load system

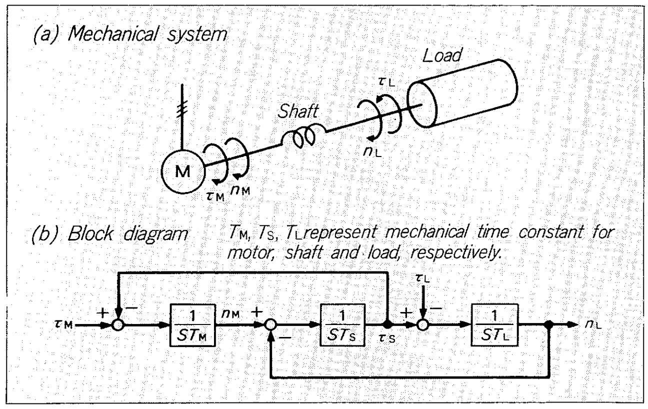
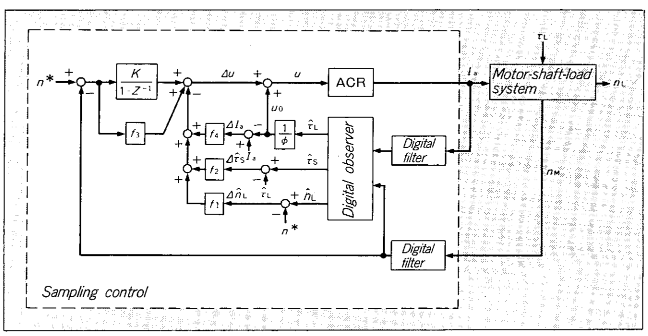


Fig. 7 Torsional vibration control system using LQI control



4.3 Application to load large in moment of inertia

4.3.1 PID control with two degrees of freedom

Among the paper making machines in a paper mill,

Fig. 8 Speed control system using PID control with two degrees of freedom

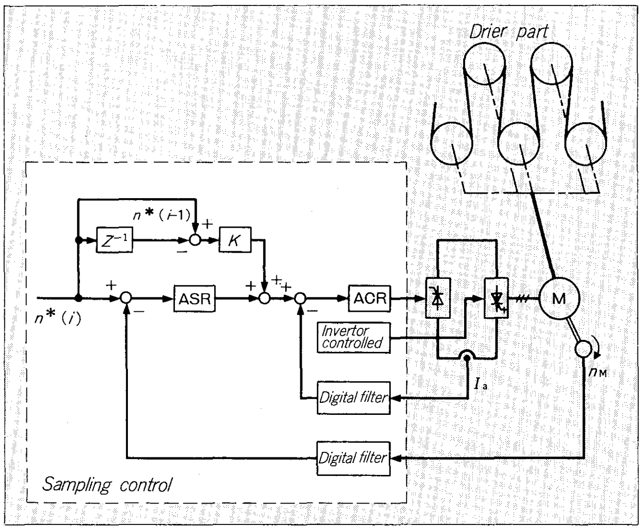
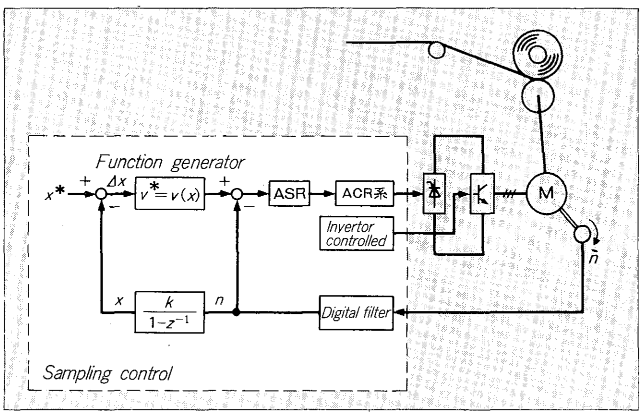


Fig. 9 Shockless control system



the drier part and calender part which are attended by specially large moment of inertia will involve the principal operational problems of how to keep pace with each other in speed control and how to restrict speed change and reduce recovery time in case of disturbances caused by breaking or threading. For speed control at uniform pace, it is necessary to improve the characteristic of following up the changes of set value. For restriction of speed changes and reduction of recovery time, it is necessary to compensate disturbances quickly. Use of the PI control type speed controller (ASR) alone, however, is not satisfactory because improvement of set-value follow up characteristic deteriorates the quick compensation of disturbances, while improvement of quick compensation of disturbances results in deterioration of follow-up characteristics. Therefore, the control system using ASR is under the necessity of aiming at a halfway control point.

A PID control with two degrees of freedom such as shown in *Fig. 8* makes it possible to improve both the follow-up characteristics and disturbance compensation characteristic. In this system, the PI-control ASR improves the disturbance compensation characteristic, while the feed forward command improves the set-value follow-up characteristics.

4.4 Shockless control

4.4.1 Positioning control using performance function

On the winder in a paper mill, the winder comes to a stop automatically (automatic slow down) when the specified windup length is reached and discharges the product. A principal problem exists in breaking and creasing caused by occurence of a shock at start point of automatic slow down.

This problem can be solved by giving a shockless speed command $v^* = v(x)$ in the control system shown in *Fig. 9*. This speed command "v^*" is determined as a solution of performance function obtained from remaining length "Δx" which is dependant on time "T" (which is under restriction of drive unit) spent until speed "v" is reduced to zero; specified length "x^*"; and position, or detected wind-up length "x".

5. CONCLUSION

In this paper, we described the application of the advanced control to the variable-speed control systems as well as the fault monitoring and diagnostics of the systems which are becoming more versatile, complex, and reliable. Under today's circumstances, were technological innovation progresses quickly especially in the filed of information technology, the variable-speed control system should also be intended to be improved by adoption of new technology; for example, AI technology which is applicable to some region where mathematical modeling of controlled object is difficult, and perfecting network systems for more efficient propagation of information. With sufficient appreciation of the situation, FUJI ELECTRIC will make continuous efforts to supply the high-quality system.