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SPECIFICATION

A MODIFIED RELAY FEEDBACK APPARATUS FOR PROCESS FREQUENCY RESPONSE ESTIMATION

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A MODIFIED RELAY FEEDBACK APPARATUS FOR PROCESS FREQUENCY RESPONSE ESTIMATION

FIELD OF THE INVENTION

The invention generally relates to the field of system identification, and more particularly to the automatic and accurate identification of multiple points on the process frequency response using a modified relay feedback apparatus.

BACKGROUND OF THE INVENTION

The current methodology for controller automatic tuning consists of a process dynamics estimation scheme and a design procedure which computes the parameters of the controller. One popular dynamics estimation scheme is a frequency response method based on the use of a relay feedback (Hagglund and Astrom (1985), "Method and an Apparatus in Tuning a PID-Regulator," U.S. Patent Number 4549123). Under a relay feedback, most processes encountered in the industry will oscillate at the ultimate frequency ω_u , where the process phase lag is 180° . The critical point of the process frequency response denoted by $g_p(j\omega_u)$, may then be obtained from a measurement of the amplitude a of the oscillation as

$$g_p(j\omega_u) = -\frac{\pi a}{4u_m},$$

where u_m is the amplitude of the relay signal and $j = \sqrt{-1}$. This critical point can be applied to tune controllers of the PID types.

There are processes whereby such a technique may yield a poor critical point estimate, for example when the process has a significant time delay or when it has underdamped dynamics. In these cases, controllers tuned on the critical point estimate can yield rather poor performance. Furthermore, the relay feedback technique only estimates one critical point. To tune more advanced controllers, accurate estimation of more points are needed. With the basic relay feedback alone, multiple experiments have to be done with different linear dynamical elements cascaded to the relay in order to estimate multiple points. This will take a considerably long time, particularly if the process has a significant time-delay.

OBJECT OF THE INVENTION

It is accordingly an object of the invention to provide a modified and improved relay feedback apparatus to overcome the deficiencies of the prior art.

It is a more specific object of the invention to provide a relay feedback apparatus including a processor apparatus configured to estimate accurately in one experiment, multiple points of the process frequency response including the critical point.

SUMMARY OF THE INVENTION

The invention is a modified relay feedback apparatus where the relay is cascaded to a new processor apparatus which in turn generates an excitation signal to the process to estimate accurately in one experiment, multiple points of the process frequency response including the critical point.

The input signal to the processor apparatus is the output of the relay. The processor is programmed to first directly connect the relay output to the process so that the system oscillates under the basic relay feedback arrangement. After a pre-specified number of relay cycles, a new signal is constructed and output to the process, by superimposing a number of sinusoids of different frequencies, the number of sinusoids equals the pre-specified number of points estimation required. The characteristics of the new signal and its constituent sinusoids can be described as follows:

- one of these sinusoids has a frequency equal to the frequency of the last relay cycle input to the processor, and the other sinusoids have frequencies that are multiples of this frequency,
- the amplitude of each sinusoid is fixed and assigned values that are suitable functions of the relay amplitude, with a lower frequency sinusoid having a greater amplitude,
- the sinusoids are superimposed at the same zero-crossing point.

This signal generation procedure is continuously responsive to the input relay signal. The processor is further programmed to monitor the oscillation of the system. When the frequency of the input relay cycles has converged within a pre-specified threshold, known Fourier Transform algorithms as given in Table 1 can be computed on the converged process input and output signals to yield the required points estimation accurately.

Where only one critical point estimation is specified, the simpler formula given in Table 2 can be used to yield the critical point.

BRIEF DESCRIPTION OF DRAWINGS

The accompanying drawings, incorporated into and forming a part of the specification, illustrate several aspects of a preferred embodiment of the present invention and, together with the description, serve to explain the principles of the invention. In the drawings :

Fig. 1a is a block diagram of the embodiment of the inventive modified relay feedback apparatus;

Fig. 1b shows the input-output characteristics of the relay in Fig. 1a;

Fig. 2 shows a flow chart for implementing the processor;

Fig. 3 is an illustration example for the estimation of one critical point;

Fig. 4 is an illustration example for the estimation of two points.

DESCRIPTION OF THE EMBODIMENTS OF THE INVENTION

In accordance with the objects and features of the invention, there is provided a modified relay feedback apparatus comprising of a new processor apparatus.

The new apparatus incorporating the novel processor apparatus will be described with reference to the accompanying drawings. Fig. 1a shows, in block diagram form, the embodiment of the inventive modified relay feedback apparatus. The processor apparatus is indicated at reference numeral 10, surrounded by a dotted outline in Fig. 1a. Reference numeral 10 represents a processor implementing programs in accordance with the flow chart shown in Fig. 2. The process variable y of process and the setpoint r are input to a summing element 14. As seen in the Figure, the process variable y is input to an inverting (subtracting) input of element 14. The output e of summing element 14 thus representing a difference between the setpoint r and the process variable y . The output of summing element 14 is input to a relay 16. The relay output a signal in accordance with the signal e in a manner as illustrated in Fig. 1b. Herein, u_m is the pre-specified amplitude of the relay signal v and u_r is the known steady state process input which maintains the process variable y at the setpoint r prior to the setup of the inventive apparatus. These, as well as other functions of the relay, are part of the prior art and accordingly a detailed description will be omitted. The output of relay 16 is

input to the processor apparatus 10 and the output of processor apparatus 10 is input to the process 12.

As hereinabove noted, the physical implementation of the modified relay feedback apparatus is preferably by means of a microprocessor/ digital-computer using known techniques to implement various aspects of the above described function. However, as will be appreciated by those of ordinary skills in the art, analog electronic circuits may be used for this purpose.

For the preferred digital implementation of the modified relay feedback apparatus, an interface between the (digital) processor apparatus and relay and the analog (input) measurements and actuator (output) signals uses analog-to-digital and digital-to-analog converters, respectively, in the same manner as used by conventional digital controllers. Accordingly, the present disclosure omits description of such converters. Similarly, the functions of the relay and the processor are implemented as a software program (stored in a Programmable Read Only Memory of the microprocessor/digital-computer, for example) for processing the stored data representing the converted input and output signals. The software used for this purpose by the present invention is the same as in other digitally implemented controllers and, accordingly, a detailed description thereof is omitted.

In the following disclosure, there is described a novel portion of the modified relay feedback apparatus, specifically the processor apparatus 10. The input signals to the processor apparatus are the output of relay 16 and the process variable y . For the preferred digital implementation, the relay output can be directly connected to the processor apparatus 10. The same computer may perform the functions of relay 16 and processor 10, or separate processors may be used. Such multiprocessing arrangements are known in the art and no elaboration is required. The output signal from the processor apparatus 10 can be converted to an analog signal by a digital-to-analog converter before connection to the actuator of process 12.

The processor apparatus 10 of the invention is programmed to operate in accordance with a flow chart shown in Fig. 2. In the flow chart of Fig. 2, k is a program counter used to count the number of samplings taken place, and accordingly, notation such as $y(k)$ represents the value of a variable y at the sampling instant kh where h is the sampling interval.

The program counters k, l and m are first initialized to zero. At step 21, the processor 10 is initialized to output

$$u(k) = v(k - 1),$$

so that the relay signal v is being connected to the process 12. At step 22, the processor 10 checks the input relay signal v to see if it has switched up. (The signal v is described

as having switched up if it switches from the lower level $u_r - u_m$ to the higher level $u_r + u_m$.) If not so, it continues to output $u(k) = v(k - 1)$ to the process 12 in step 23 and returns to step 22. It will be apparent to those familiar with digital systems that the loop comprising step 22 and step 23 is functioning as a polling loop to detect switching up of the relay signal v . The detection of switching up occurrence is only one possible implementation of the step used for the illustration of the invention here. Alternatively, the processor 10 may be programmed to detect switching down occurrence.

Once the relay signal v switches up, step 24 will be executed in which the program counter l is incremented by one to indicate the number of times the relay signal v has switched up. The time corresponding to the l^{th} switch will be stored in a memory array T as

$$T(l) = kh.$$

Next, step 25 will be executed in which the processor 10 will check the number of times relay signal v has switched up so far from the program counter l . If l is less than a pre-specified number N_{sw} , the program flow will be looped back to step 23, otherwise step 26 will be executed next.

At step 26, the program counter m is incremented by one. The most recent frequency $\omega_v(m)$ corresponding to the counter m is computed as

$$\omega_v(m) = \frac{2\pi}{T(l) - T(l - 1)}.$$

Next at step 27, the processor 10 will determine whether the frequency measurements ω_v has converged. Numerous judging techniques may be used to implement such a determination, such as determining that the percentage change in the magnitude of the preceding two estimates is below a specified threshold. If the frequency measurements of ω_v has converged, then step 28 will be executed, otherwise step 29 instead will be executed.

At step 28, a new signal will be constructed from a superimposition of N_{pt} sinusoids as

$$u(k) = u_r + \sum_{n=1}^{N_{pt}} a_n \sin n\omega_v(m)(kh - T(l)),$$

where N_{pt} is a pre-specified number of points to be estimated and $a_n = \frac{4u_m}{n\pi}$ is the amplitudes associated with the respective sinusoids. Similar types of relation between a_n and u_m may be used, but they should be subject to $a_{n1} > a_{n2}, n1 < n2$. Note that the sinusoids are superimposed at the same zero crossing point.

Next, step 210 performs the same function as step 22 to check for up switches of relay signal v . The loop comprising of step 28 and step 210 is another polling loop.

If an up switch is detected, step 211, similar in function to step 24, will be executed before connecting back to the flow chart at step 26.

Finally, step 29 will compute the points estimation from the last cycle of the excitation signal u and the corresponding process variable y . If multiple points estimation are required, $N_{pt} > 1$, then the formulae given in Table 1 will be used for the computation, otherwise, the formula given in Table 2 will be used for the computation of the critical point.

Accordingly, the flow chart of Fig. 2 provide for an automatic and accurate estimation of a single critical point or multiple points specified by the user of the invention

The improvement in the accuracy of the single critical point estimation can be explained by an analysis of the modified relay feedback apparatus. In the steady state oscillation of the experiment, the input and output of the process 12 are two pure sinusoids of the same frequency, out of phase by 180° . The oscillating frequency must thus be at the ultimate frequency and the critical point can be obtained exactly from the formula given in Table 2.

The estimation of multiple points in one experiment may also be explained from a signal analysis of the modified relay feedback apparatus. In the steady state oscillation of the experiment, the input and output of the process are two signals consisting of a number of sinusoidal components with frequencies that are multiples of the oscillation frequency. Known Fourier Transform algorithms performed on these signals will thus yield the same number of points at the respective frequencies on the process frequency response. In this case, since the input and output signals of the process are not pure sinusoids, the oscillation frequency may not be at the exact ultimate frequency so that the critical point may not be exactly obtained. However, it can be appreciated that the accuracy of the critical point thus obtained will be better than the prior art since in the latter, the input signal to the process is a pulse signal generated by the relay which consists of an infinite number of sinusoids, much more than the finite pre-specified number of sinusoids used in the new invention.

To further illustrate the principles of the invention, a simulation example of the inventive approach for the estimation of one critical point is shown in Fig. 3. In the simulation, the process is given by

$$g_p(s) = \frac{1}{s+1} e^{-10s},$$

and the various pre-specified numbers are $N_{sw} = 3$, $N_{pt} = 1$ and the relay signal frequency is required to converge to within a 5% threshold. The signals $y(t)$, $u(t)$ and $v(t)$ of the experiment are shown respectively in the top, middle and bottom frames in Fig. 3. The relay signal v is output to the process from $t = 0$ to $t = 52$ before the third

relay up switch. After the third relay up switch to $v = u_m$ at $t = 52$, the processor constructs and outputs the new sinusoidal signal. The oscillation converges to within the 5% threshold after two subsequent oscillations to yield the critical point estimate as

$$g_p(0.29j) = -0.960,$$

which is almost an exact estimate of the true critical point of the process given by $g_p(0.29j) = -0.962$.

Another simulation example of the inventive approach for the estimation of two points is shown in Fig. 4. In the simulation, the same process given by $g_p(s) = \frac{1}{s+1}e^{-10s}$ is used and the various pre-specified numbers are $N_{sw} = 3$, $N_{pt} = 2$ and the relay signal frequency is similarly required to converge to within a 5% threshold. The signals $y(t)$, $u(t)$ and $v(t)$ of the experiment are shown respectively in the top, middle and bottom frames in Fig. 4. The relay signal v is output to the process from $t = 0$ to $t = 52$ before the third relay up switch. After the third relay up switch to $v = u_m$ at $t = 52$, the processor constructs and outputs the new signal made up of two sinusoids. The oscillation converges to the 5% threshold after three subsequent oscillations to yield the points

$$\begin{aligned} g_p(0.27j) &= -0.95 - 0.14j, \\ g_p(0.54j) &= 0.83 + 0.27j. \end{aligned}$$

Note that $g_p(0.27j)$ is the estimate of the process critical point.

The foregoing description of the preferred embodiment of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed, since many modifications or variations thereof are possible in light of the above teaching. All such modifications and variations are within the scope of the invention. The embodiments described herein were chosen and described in order best to explain the principles of the invention and its practical application, thereby to enable others skilled in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated thereof. It is intended that the scope of the invention be defined by the claims appended hereto, when interpreted in accordance with the full breadth to which they are legally and equitably entitled.

ATTACHMENT TABLES

Table 1. Formulae to estimate $N_{pt} > 1$ points of the process frequency response $g_p(j\omega)$ from the periodic input (u) and output signals (y) with fundamental frequency ω^* .

$$g_p(jn\omega^*) = \frac{\int_{-\frac{t^*}{2}}^{\frac{t^*}{2}} y(t) e^{-jn\omega^* t} dt}{\int_{-\frac{t^*}{2}}^{\frac{t^*}{2}} u(t) e^{-jn\omega^* t} dt}, \quad n = 1 \dots N_{pt},$$

where $t^* = \frac{2\pi}{\omega_0}$ and $j = \sqrt{-1}$.

Table 2. Formula to estimate one critical point of the process frequency response $g_p(i\omega)$ from the periodic input (u) and output signals (y) with fundamental frequency ω^* . The amplitudes of the input and output signal are a_u and a_y respectively.

$$g_p(j\omega^*) = -\frac{a_y}{a_u}.$$



Claims

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows :

1. In a relay feedback apparatus having input means for inputting a first signal representing a setpoint for a process and a second signal representing a process variable, means for generating an error signal representing a difference between said first and second signals, and relay means for providing a relay signal to the process as a function of said error signal, the improvement comprising :
 - processor means connected to receive said relay signal for generating an excitation signal to the process;
 - said processor means including :
 - program determining first means to determine whether to output said relay signal or a new signal;
 - program determining second means to determine whether the oscillation of said relay signal has sufficiently converged;
 - program computation means to compute the required points of the process frequency response when said program determining second means determines that the oscillation of said relay signal has sufficiently converged .
2. A modified relay feedback apparatus as recited in claim 1, wherein said program determining first means comprises a sequence of program steps to monitor the number of relay up switches that has occurred,
 - whereby said new signal generated by a signal means is output as said excitation signal if said number of relay up switches exceed a first pre-specified number, and
 - said relay signal is output as said excitation signal if said number of relay up switches does not exceed said first pre-specified number.
3. A modified relay feedback apparatus as recited in claim 2, wherein said signal means comprises a sequence of program steps to construct said new signal composing of a number of sinusoids of different frequencies superimposed,
 - whereby the number of sinusoids equals a second pre-specified number of points to be estimated,



- one of the said sinusoids is assigned the frequency of the last cycle of said relay signal input, and the other said sinusoids are assigned the next immediate multiples of this frequency,
 - the amplitudes of said sinusoids are functions of the amplitude of said relay signal,
 - the amplitude of a lower frequency sinusoid is assigned a greater value than the amplitude of a higher frequency sinusoid, and
 - said sinusoids are superimposed at the same zero crossing point.
4. A modified relay feedback apparatus as recited in claim 1 wherein said program determining second means comprises a sequence of program steps to determine the magnitude of the percentage change in the frequency of the last two cycle of said relay signal,
- whereby said relay signal oscillation is determined as not having sufficiently converged if said magnitude exceeds a third pre-specified number, and
 - said relay signal oscillation is determined as having sufficiently converged if said magnitude does not exceed said third pre-specified number.
5. A modified relay feedback apparatus as recited in claim 1 wherein said program computation means comprises :
- a sequence of program steps for executing known Fourier Transform algorithms given in Table 1 on said new signal and said second signal to obtain the points if said second pre-specified number of points to be estimated is more than one, and
 - a sequence of program steps for executing the formula given in Table 2 to obtain the critical point if said second pre-specified number of points to be estimated equals one.

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ABSTRACT

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A modified relay feedback apparatus which facilitate an accurate and automatic identification of multiple points on the process frequency response, including the critical point, in one experiment. It uses the basic relay feedback apparatus with additionally, a new processor apparatus cascaded to the relay. The thus modified apparatus is useful in the context of automatic tuning and it is applicable to a wide range of industrial processes.



DRAWINGS

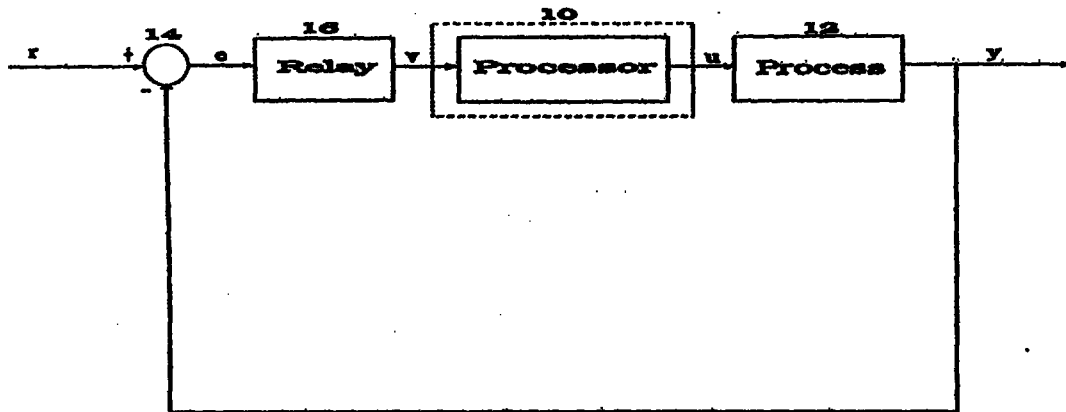


Fig. 1a : Block diagram of the embodiment of the inventive modified relay feedback apparatus.

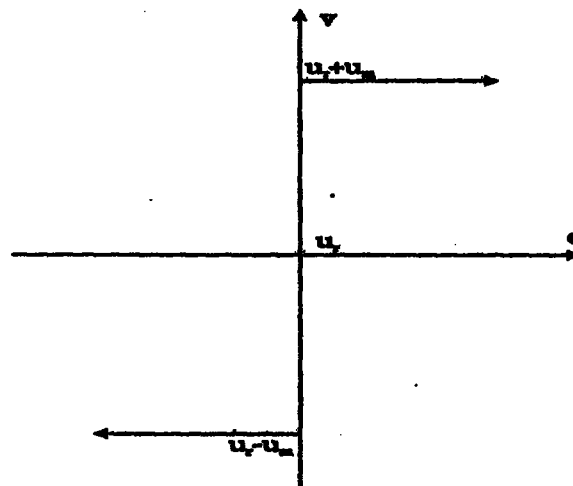


Fig. 1b : Input-output characteristics of the relay in Fig. 1a.

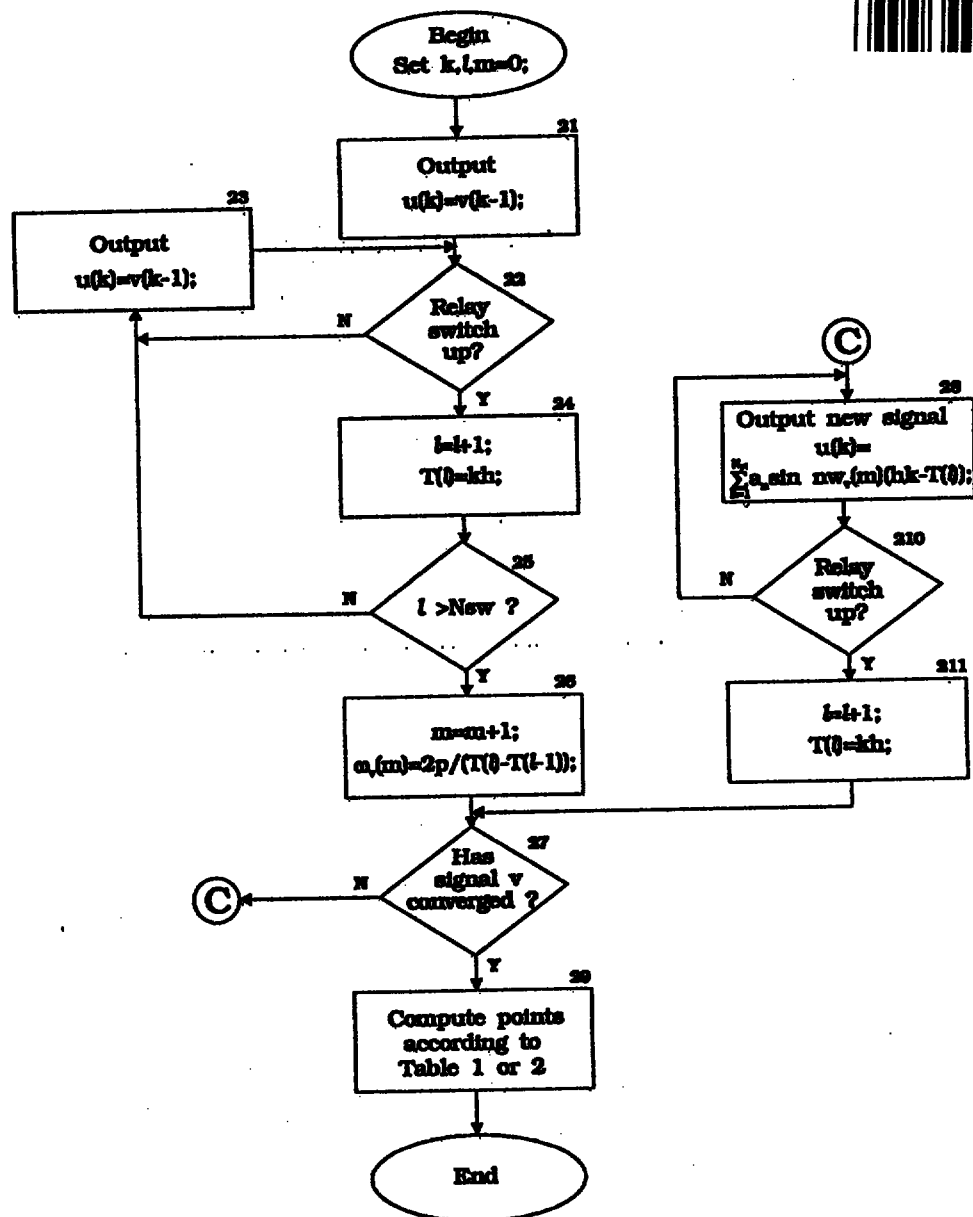


Fig. 2 : flow chart for implementing the processor apparatus.

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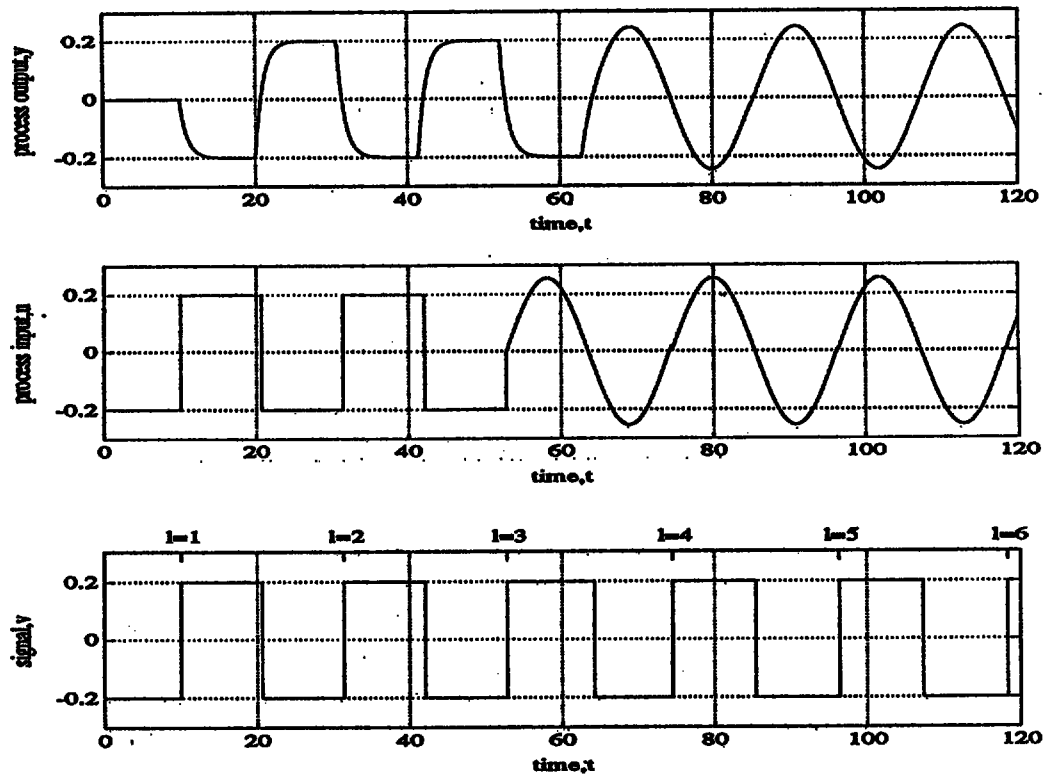


Fig. 3 : An illustration example for the estimation of one critical point.

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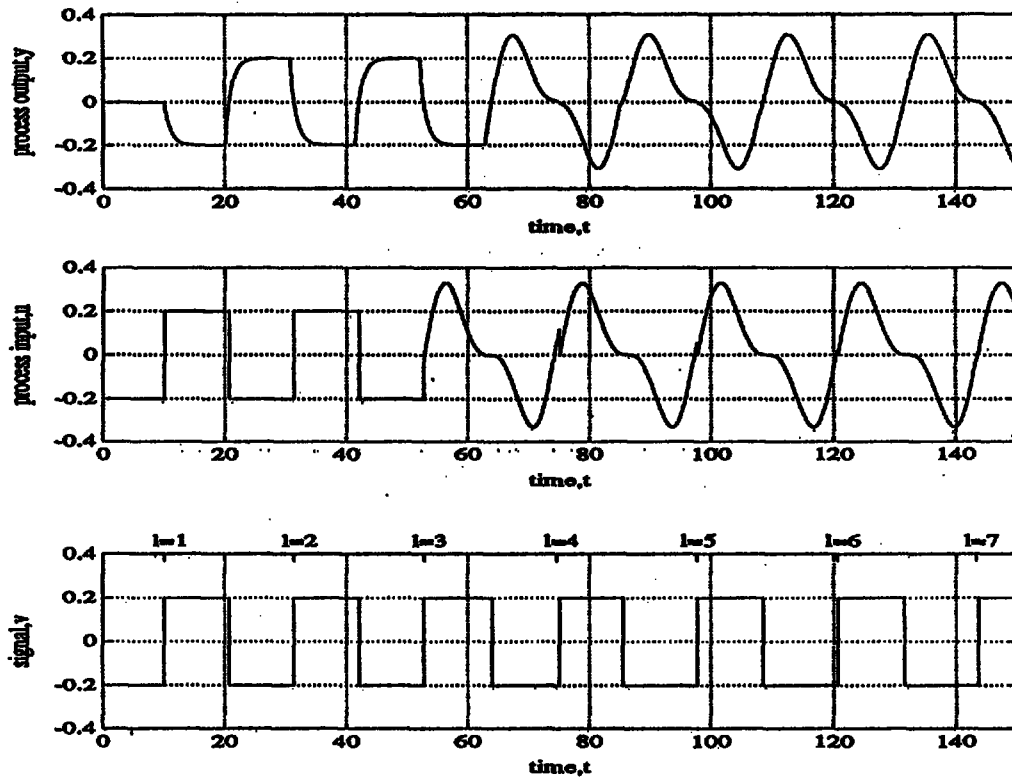


Fig. 4 : An illustration example for the estimation of two points.

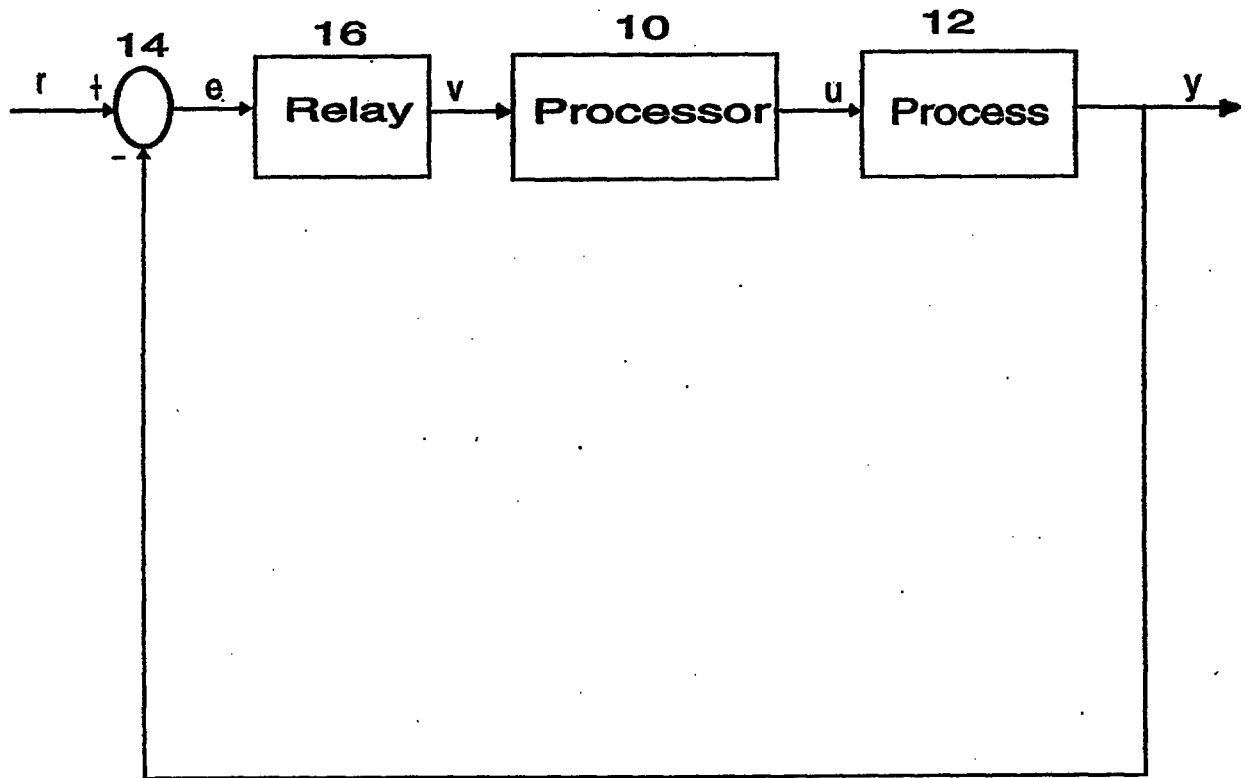


Fig. 1a : Block Diagram of the embodiment
of the inventive relay feedback
apparatus.

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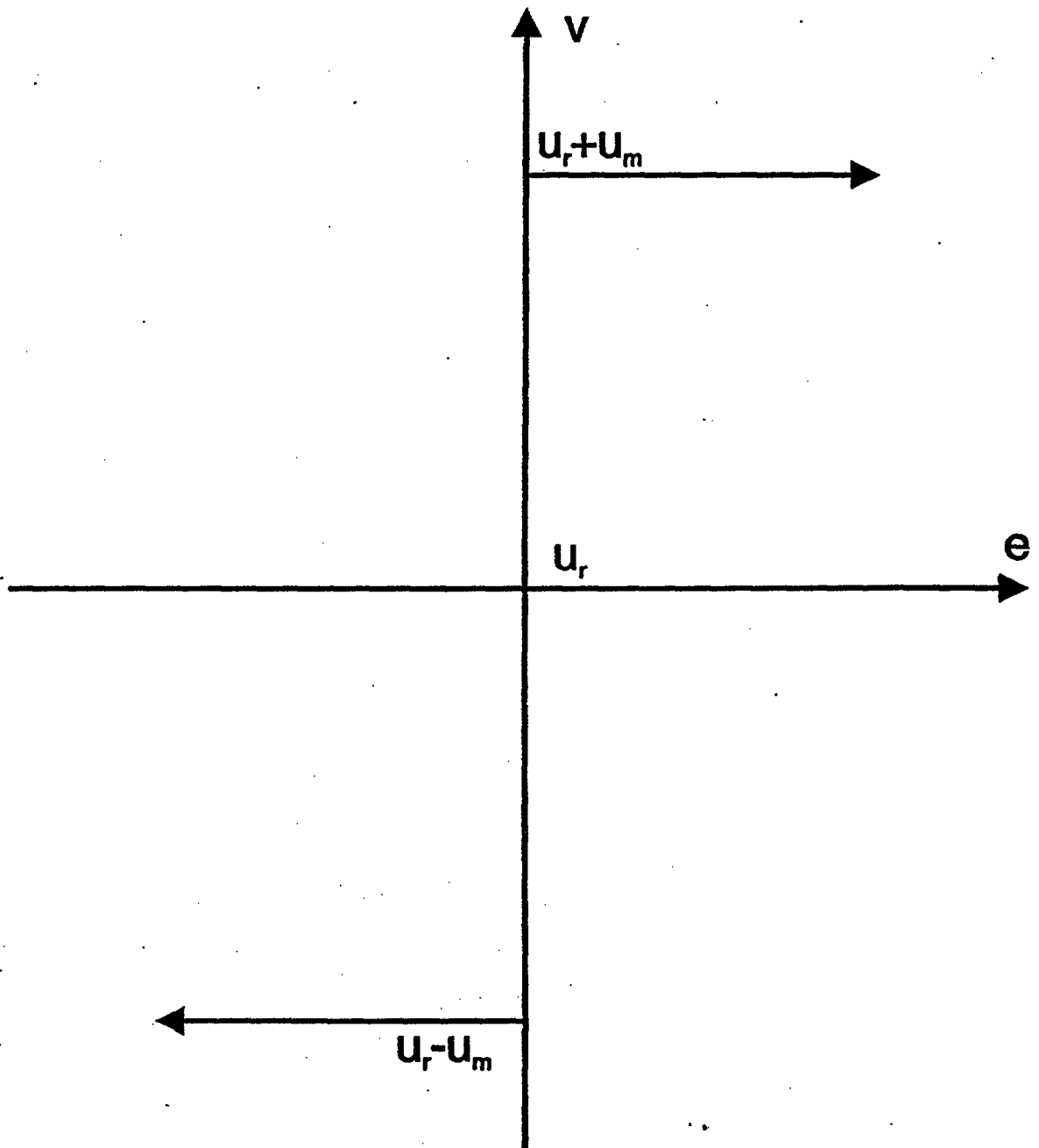


Fig. 1b : Input-output characteristics of the relay in Fig. 1a.

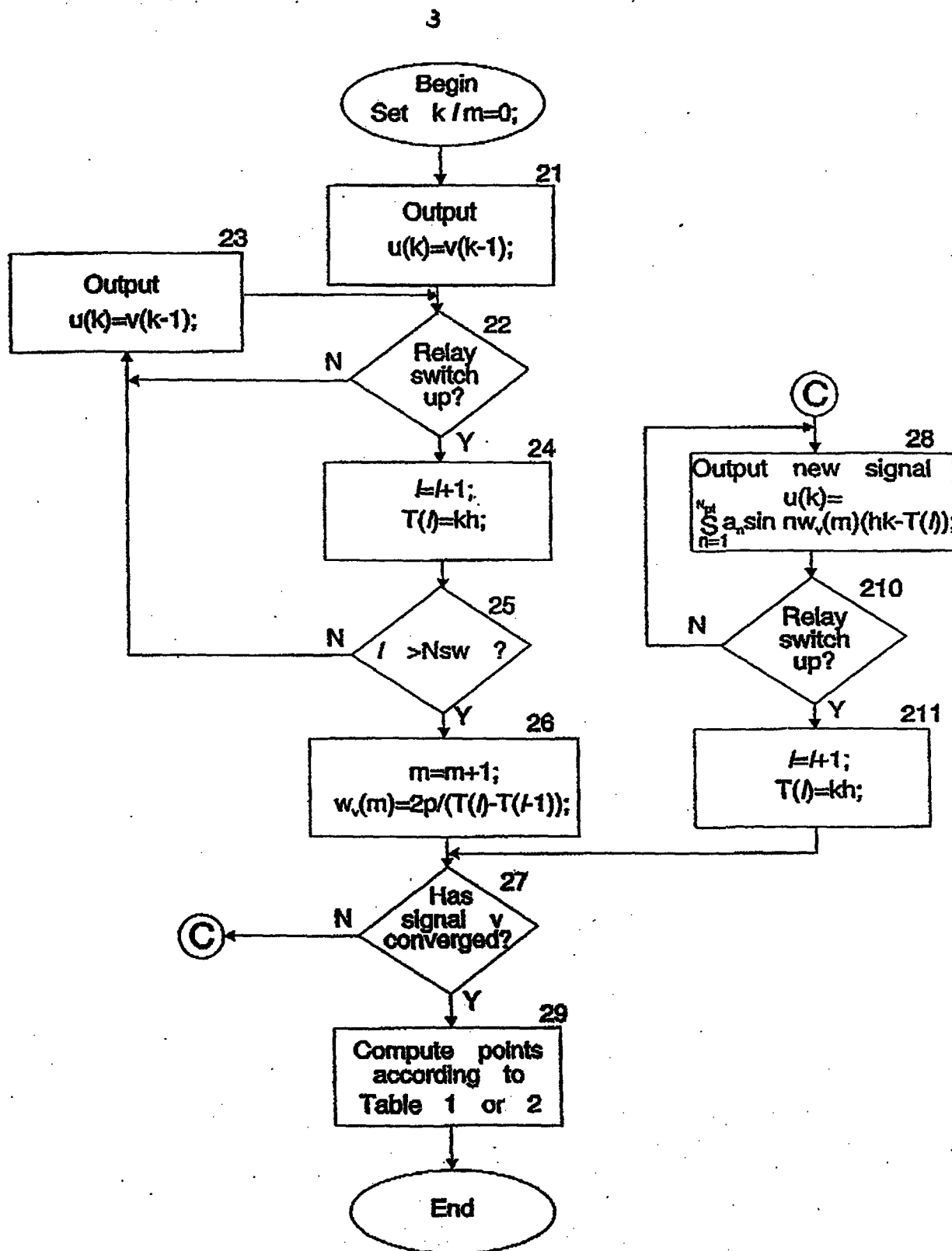


Fig. 2: Flow chart for implementing the processor apparatus.

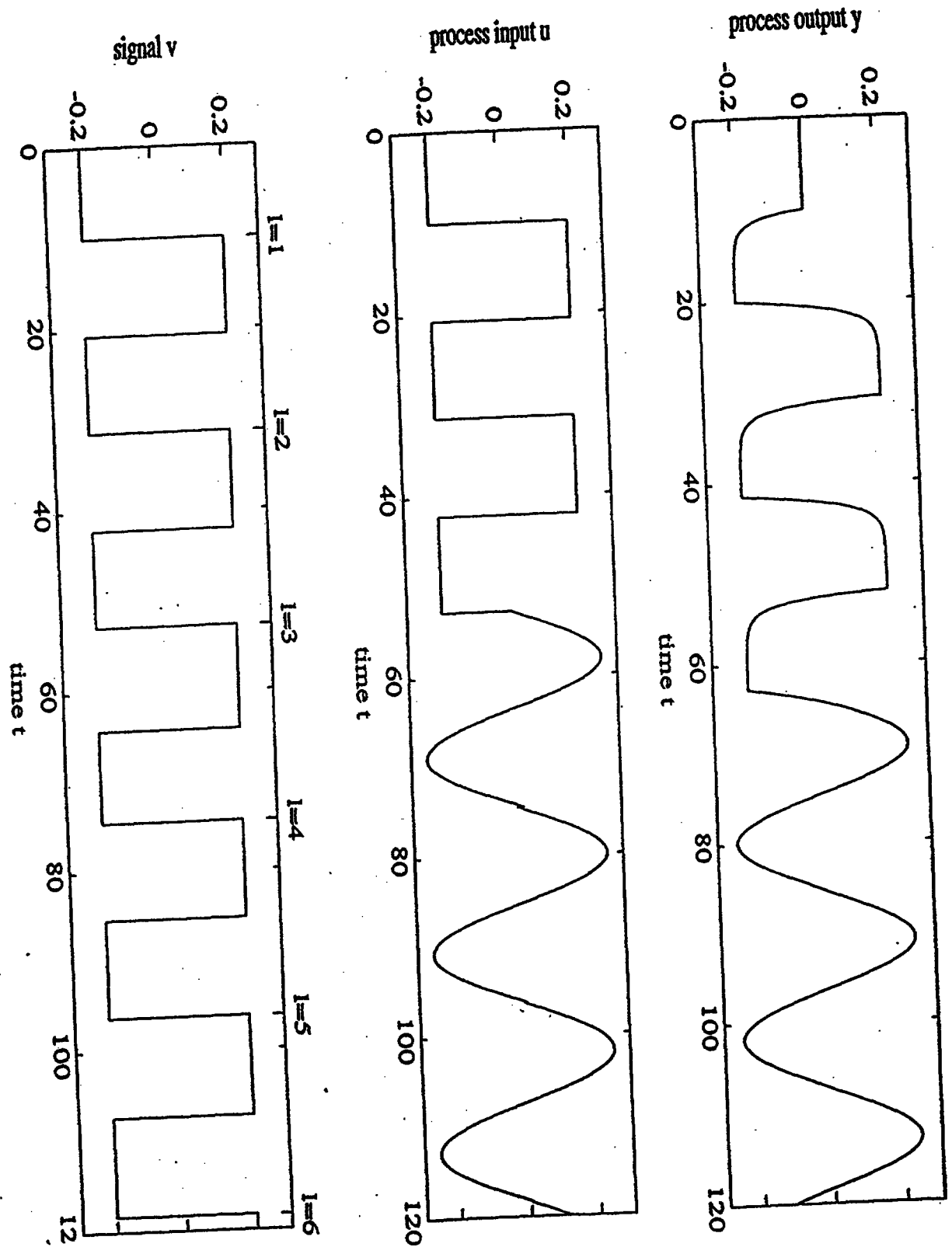


Fig. 3 : An illustration example for the estimation of one critical point.

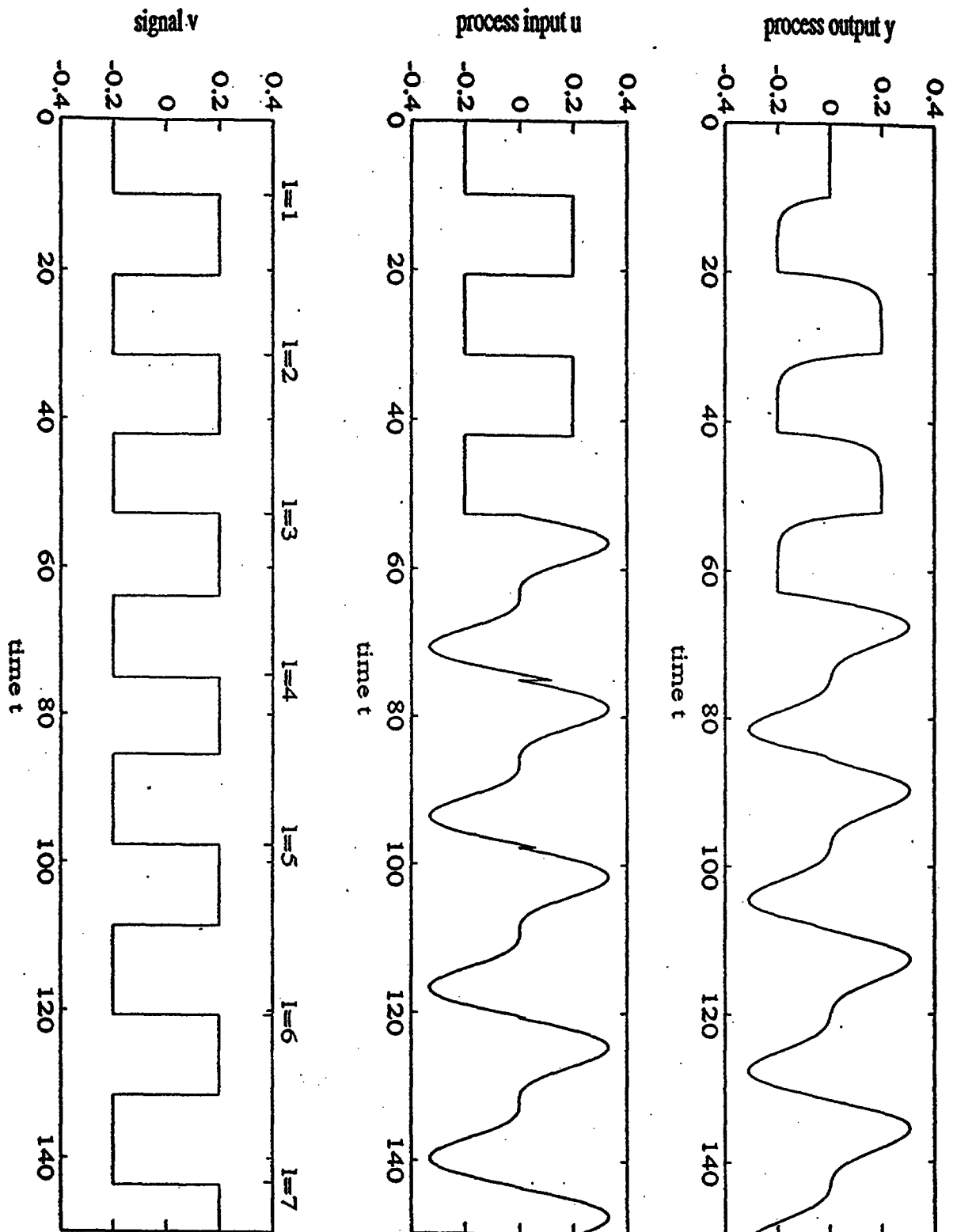


Fig. 4 : An illustration example for the estimation of two points.

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ABSTRACT**A MODIFIED RELAY FEEDBACK APPARATUS FOR PROCESS
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A modified relay feedback apparatus which facilitates an accurate and automatic identification of multiple points on the process frequency response, including the critical point, in one experiment. It uses the basic relay feedback apparatus with additionally, a new processor apparatus cascaded to the relay. The thus modified apparatus is useful in the context of automatic tuning and it is applicable to a wide range of industrial processes.

(Fig 1a, Fig 1b & Fig 2 are to be published)

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