Logic and Method of Safety in Controlling a Power Press

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The Ministry of Labor in Japan has established a standard for the mechanical structure of power presses. The standard stipulates that the power press be equipped with an overrun monitor function that enables the slide to be forcibly stopped when the slide fails to stop within a specified allowable range around the top dead center. The operation of the power press is considered to be a man–machine system in which both the operator and the machine may make errors. The overrun monitor function is defined as a requirement for safe operation of the system. A signal processing method is established for fail-safe operation of the overrun monitor function. A fail–safe overrun monitor system based on the signal processing method is presented.

Key Words: Safety Engineering, Industrial Machine, Control Device, Press Working, Interlock, Fail–Safe, Overrun Monitor

1. Introduction

Japan has nearly 5,000 power press accidents per year (1986 survey). Thus the Ministry of Labor has established the Standard for the Structure of Power Presses1 to enhance the safety of work with power presses.

In Article 27 of the Standard, the function that forcibly stops the slide of the mechanical press when the slide fails to stop within the specified range of the top dead center is called overrun monitoring. Article 2 states that each mechanical press must be equipped with an emergency stop mechanism and must have a function such that the slide cannot start unless the specified starting procedure is implemented after the actuation of the emergency stop mechanism.

In Section 2 of this paper, a mechanical press work system is defined as a man–machine system in which both the machine and the human operator may make errors2. It is logically demonstrated that the safety of work with the mechanical press must be ensured by the configuration (interlock)3 of the above–mentioned overrun monitoring function and an optical safety device that inspects for safety by projecting a light beam in front of the bolster. For positive overrun monitoring, it is necessary to detect the off state of the run buttons. In other words, Article 2 above must be applied to each cycle of slide operation. The detection of the off state of the run buttons is called the antirepeat function.

In Section 3, each slide cycle is divided into the down stroke and up stroke of the press control sequence. In addition, an inspection stroke is provided for the slide when changing from the up stroke to the down stroke. The section in which the inspection is performed is called the operation preparation section for the slide to move down. The necessary conditions for this operational preparation are overrun monitoring and confirmation of the run button off state, described in Section 2. Also discussed are the nature of the signals generated in the operation preparation.
section (operation preparation signals) and the characteristics of the slide position signals required for generating the operation preparation signals.

Section 4 indicates the method of generating overrun monitoring and run button off-state confirmation signals as concrete operation preparation signals, using fail-safe AND elements. The fail-safe AND element is an AND gate that produces no output when the circuit itself fails\(^4\).

2. Logic Structure of Safety Confirmation in Mechanical Presses

2.1 Safe work system with consideration of errors by both machine and operator

Safety assurance by the overrun monitor to determine the operating conditions of the press according to the operating sequence of the slide, and by the optical sensor located in front of the bolster, is considered important for the mechanical press.

A work system with a mechanical press is regarded here as a man-machine system in which both the machine and operator may make errors\(^5\). The conditions under which safety is assured in the mechanical press are logically discussed, and the engineering position of the two safety devices is established.

Let \( S \) be the space in which the operator and movable machine part work (space on the bolster in the case of the press), \( H(t) \) be the binary logic variable that indicates the presence or absence of the operator in the work space \( S \) at the time \( t \), and \( M(t) \) be the binary logic variable that indicates the presence or absence of the movable machine part in the work space \( S \) at the time \( t \). Then,

\[
H(t) = 1: \text{ The operator is working in the space } S \text{ at the time } t.
\]

\[
H(t) = 0: \text{ The operator is not working in the space } S \text{ at the time } t.
\]

\[
M(t) = 1: \text{ The movable machine part is working in the space } S \text{ at the time } t.
\]

\[
M(t) = 0: \text{ The movable machine part is not working in the space } S \text{ at the time } t.
\]

Given the pattern in which the operator or movable machine part is present in the work space \( S \), the subscript \( s \) indicates that the operator or movable machine part is in the work space \( S \) as a correct mode of operation, while the subscript \( f \) indicates that the operator or movable machine part is accidentally present in the work space \( S \) due to failure or noise.

\[
H_s(t) = 1, M_s(t) = 1: \text{ The operator or movable machine part is working in the work space } S \text{ at the time } t, \text{ in a correct mode of operation.}
\]

\[
H_f(t) = 1, M_f(t) = 1: \text{ The operator or movable machine part is working in the work space } S \text{ at the time } t, \text{ in an incorrect mode of operation.}
\]

\[
H_f(t) = 0, M_s(t) = 0: \text{ The operator or movable machine part is not working in the work space } S \text{ at the time } t, \text{ in a correct mode of operation.}
\]

\[
H_f(t) = 0, M_f(t) = 0: \text{ The operator or movable machine part is not working in the work space } S \text{ at the time } t, \text{ in an incorrect mode of operation.}
\]

If the above incorrect operations are taken into account, the work of the operator or movable machine part may be either normal or abnormal. The work condition \( H(t) \) or \( M(t) \) in the work space \( S \) at the time \( t \) is represented by

\[
H(t) = H_s(t) \lor H_f(t),
\]

\[
M(t) = M_s(t) \lor M_f(t).
\]

where the symbol \( \lor \) denotes an OR operation.

An accident occurs in the man-machine system when the operator and movable machine part work in the same space at the same time or collide with each other. For safe work execution, \( H(t) \cdot M(t) = 0 \) or the following equation must hold at any time \( t \) :

\[
(H_s(t) \lor H_f(t)) \cdot (M_s(t) \lor M_f(t)) = (H_s(t) \cdot M_s(t)) \lor (H_f(t) \cdot M_f(t)) \lor (H_s(t) \cdot M_f(t)) \lor (H_f(t) \cdot M_s(t)) = 0,
\]

where the symbol \( \cdot \) denotes an AND operation.

Equation (2) means that when the operator and machine share the same work space, they must not collide with each other, irrespective of whether or not they correctly operate. This is the principle of safe work.

If the work system is set to satisfy the above principle of safe work, \( H(t) \cdot M(t) = 0 \) should be satisfied when the operator and machine correctly operate. If the principle of safe work is to be satisfied despite occurrence of incorrect operation, the following condition (or condition under which safety is assured despite incorrect operation) must hold:

\[
(H_s(t) \cdot M_f(t)) \lor (H_f(t) \cdot M_s(t)) = 0.
\]

As the first method of safety assurance, Eq. (3) holds at least when there are no incorrect operator and machine operations or when there are no \( H_s(t) = 1 \) and \( M_s(t) = 1 \). This means that the operator and machine should both be fail-safe (or should not start working incorrectly), or that \( H_f(t) = 0 \) and \( M_f(t) = 0 \). This man-machine work system can be represented by a configuration such that the output of the movable machine part is produced after the absence of the operator in the work space is detected and that the operator starts to work after he confirms the absence of the movable machine part in the work space. This is called the interlock configuration of the man-machine system. If \( m(t) \) is the binary logic variable for the work command given to the movable machine part, \( M(t) \) is the binary logic variable for the output.
of work execution, $h(t)$ is the binary logic variable for the work intention of the operator, and $H(t)$ is the binary logic variable for the action of the operator to perform the work, safety assurance can be represented by

$$H(t) = h(t) \cdot \neg M(t)$$
$$M(t) = m(t) = H(t)$$

where the symbol $\neg$ denotes a NOT operation.

As the second method, Eq. (3) is given as the sum of the three logic products $H_i(t) \cdot M_i(t)$, $H_i(t) \cdot M_j(t)$, and $H_i(t) \cdot M_k(t)$. When this sum is logic 0, safety can be assured even if an incorrect operation occurs of $H_i(t)=1$ or $M_i(t)=1$. When the incorrect operation of $H_i(t)=1$ occurs, for example, safety is assured unless the movable machine part operates $M_i(t)=1$ or $M_j(t)=1$. When the incorrect operation of $M_i(t)=1$ occurs, safety is assured unless the operator starts working $[H_i(t)=1$ or $H_i(t)=1]$. The safety assurance configuration based on Eq. (3) requires that the machine have the functions of detecting the absence of the operator in the work space and of not accidently producing output, and that the operator have the functions of detecting the absence of the movable machine part in the work space and of not accidently entering the work space. In reality, however, it is essentially impossible for the operator to work without any errors. Neither can the machine always generate the work command $[m(t)]$ without errors. In the man-machine work system, it is assumed that the operator does not collide against the movable machine part by design, allows the movable machine part to work only when the operator is absent from the work space, and implements some method to prevent the machine from operating incorrectly.

Figure 1 schematically illustrates the man-machine system that allows for errors in the safety confirmation and judgment of the operator and thus does not depend on the safety confirmation or judgment of the operator (for example, visual safety confirmation and judgment).

In Fig. 1, S is the work space in which the operator and movable machine part work together, IM 1 is the sensor that detects the absence of the operator in the work space, IM 2 is the sensor that detects the absence of faults in the machine [in the case of the mechanical press, a controller to produce the work command $m(t)$], and GM 1 and GM 2 are AND gates that execute the judgment function. When the sensor IM 1 confirms the absence of the operator from the work space, the machine output $m(t)$ generates the output command $M_1(t) = m(t) \cdot \neg H(t)$ according to the judgment of the sensor IM 1. When the sensor IM 2 confirms that the machine is normal, the output command $M_2(t)$ generates the work execution command $M(t)$ so that no output is produced while the operator is working in the work space. If the sensor IM 2 and associated AND gate GM 2 are realized with such characteristics that they do not incorrectly produce the work execution output $M(t)$ (false-safe output characteristics), the machine execution output $M(t)$ is given by

$$M(t) = m(t) \cdot \neg H(t) \cdot M_2(t).$$

Equation (5) means that the output $M(t)$ follows the command $m(t)$ only when the operator is not present in the work space $[-H(t)=1]$ and the machine is normal $[M_2(t)=1]$. $M_2(t)$ is the binary logic variable that denotes the operating state of the machine. It becomes 1 when the machine is normal and 0 when the machine is faulty.

If the mechanical press is to satisfy Eq. (5) as a safe man-machine work system, it must have the functions of sensing that no part of the operator's body is present on the bolster [or confirming $-H(t)$ $=1$] and that the machine is normal [or confirming $M_2(t)=1$]. The mechanical press realizes the former and latter functions by means of an optical sensor and a fail-safe overrun monitor, respectively. The optical sensor has a light beam projecting in front of the bolster. As soon as the light beam is interrupted by any part of the operator's body while the slide is moving down, the optical sensor stops the lowering slide. The overrun monitor produces a slide lower output signal only when the machine, including the sensor IM 1 and AND gate GM 1, is normal, and confirms the brake function so that the slide can be stopped when necessary.

2.2 Method of overrun monitoring and confirming run button off state

The overrun monitoring function of the mechanical press is confirmed when the slide rises and stops within the specified range of the top dead center. In general machine systems, it is difficult to determine whether or not objects have completely stopped. In the mechanical press, this judgment is made by confirming the position of the slide when the slide is restarted after it is stopped on the up stroke. A mechanical
press with 150 strokes or less per minute, for example, is required to have such a configuration that the slide can be restarted when it is stopped at a crank angle of within 15° around the top dead center, and cannot be restarted when it is stopped at a crank angle of over 15° around the top dead center.

The following functions are important for the above method of overrun monitoring:

1. The slide drive power is always turned off at the desired position on the up stroke.
2. The run buttons are turned off when the slide is to be restarted.

Function (1) means that an overrun condition (or condition in which the slide stops at the crank angle of over 15°) cannot be detected if the slide drive power is interrupted too early. Any error in the delay of this interruption is allowed. Function (2) means that when the run button incorrectly turns on, the slide is restarted as it goes over the top dead center even if the brake performance is deteriorated, creating an overrun condition. In other words, confirmation of the run button off state on the up stroke of the slide must be added as a press operating condition (this is commonly called the antirepeat function).

Safe work with the mechanical press calls for at least the function of moving the slide only when no part of the operator's body is present on the bolster and functions for confirming the capacity of the brake and the off state of the run buttons so that the slide cannot be moved mistakenly by the operator. These functions must be realized by a fail-safe configuration (or such a configuration that the slide does not move down when it is faulty). The latter functions are addressed here.

3. Control and Signal Processing for Safety Assurance

3.1 Slide position signals

Here, the "safety cycle" method, defined in JIS B 0111 - Glossary of Terms for Presswork Machinery (1991) and often used for the manual operation of mechanical presses, is considered. Once the two run buttons are pressed simultaneously with the slide positioned at the top dead center, the slide then lowers, rises, and stops again at the top dead center, irrespective of whether or not the run buttons are pressed thereafter. This is a normal cycle of press operation. Under the safety cycle method, the slide on the down stroke moves as long as the run buttons are both pressed and stops as soon as either run button is released. The control sequence of the press during the safety cycle can be represented in terms of the crank angle, as shown in Fig. 2 (a). The top dead center is the highest position the slide can reach (crank angle = 0°), and the bottom dead center is the lowest position the slide can reach (crank angle = 180°). The section S_1 from the crank angle θ_1 to θ_2 is that in which the slide lowers, the section S_2 from the crank angle θ_2 to θ_3 is that in which the slide rises, and the section S_0 from the crank angle θ_3 to θ_4 is that in which the slide is first readied and then lowered for the next cycle. The section S_0 is called the operation preparation section.

The magnitude of the output energy of the press is controlled to be different values at the crank angles θ_1 to θ_2. The sections S_1, S_2, and S_3 are controlled in different manners for safety assurance. Namely, S_1 is the slide lowering section, in which the slide must be stopped when any part of the operator's body is present on the bolster. S_2 is the safety section where the slide automatically rises and, conversely, the crank must not rotate. S_0 is the operation preparation section, in which the slide is monitored for overrun, the off state of the run buttons is confirmed, and the slide is restarted based on the monitoring and confirmation. Such control of the three sections calls for at least four slide position signals, as described below.

(a) Signal P_1 confirms that the slide has stopped near the top dead center (within the crank angle θ_1).
(b) Signal P_2 interrupts the slide drive power for brake performance confirmation.
(c) Signal P_3 indicates whether the slide is on the down or up stroke.
(d) Signal P_4 confirms that the run buttons are released.

![Fig. 2 Operating sequence of mechanical press](image-url)
Signals \( P_1 \) to \( P_4 \) are called the top dead center stop confirmation signal, top dead center stop signal, up-stroke signal, and antirepeat signal, respectively.

Figure 2(b) illustrates the slide moving conditions in the operation preparation section \( S_n \), slide lowering section \( S_l \), and slide rising section \( S_r \) shown in Fig. 2(a). When the inspection conditions are satisfied in \( S_n \), the slide starts the down stroke (\( S_{na} \)). If there is no system problem in the down stroke, the slide automatically changes to the up stroke (\( S_{na} \)) and then begins the inspection stroke (\( S_{na} \)). Q_2=1 (described later) is the condition necessary for the slide to lower. In Fig. 2(b), \( S_{na} \), \( S_{ia} \), and \( S_{ia} \) are binary logic variables for the conditions in \( S_n \), \( S_l \), and \( S_r \), respectively. The binary logic variables take the value of logic 1 and allow the slide to move when the conditions are satisfied in the respective sections.

3.2 Fail-safe signal processing

Consider the signal processing circuit \( A_0 \) (Fig. 3), where the binary input signal \( f_1 \) is processed and the binary output signal \( f_0 \) is generated. The output signal \( f_0 \) is generated only when the power \( E_s \) is available, and is represented by either of the following equations:

\[
\begin{align*}
\text{Eq. (6a):} & \quad f_0 = E_s \cdot f_1 \\
\text{Eq. (6b):} & \quad f_0 = E_s \cdot \overline{f_1}
\end{align*}
\]

The power \( E_s \) is denoted by a binary logic variable that becomes 1 when the power \( E_s \) is available and 0 when the power \( E_s \) is not available. If the input signal \( f_1 \) has no error and the signal processing circuit \( A_0 \) has no fault, \( f_0 = 1 \) is produced only when the power \( E_s \) is correctly input (\( E_s = 1 \)), and \( f_0 = 0 \) includes a logic 0 error due to a power fault (\( E_s = 0 \)). Thus, \( f_0 = 1 \) contains no error. The logic relation of the output signal \( f_0 \) to the power \( E_s \) is such that if the signal processing circuit \( A_0 \) always generates \( f_0 = 0 \) when it fails, \( f_0 = 1 \) contains no error for the signal processing circuit \( A_0 \), as for the power \( E_s \). If the operating state of the signal processing circuit \( A_0 \) is denoted by the binary logic variable \( A_0^* \) (\( A_0^* = 1 \) for the normal state and \( A_0^* = 0 \) for the faulty state) on the assumption that the input signal \( f_1 \) has no error, the output signal \( f_0 \), containing the operating state of the signal processing circuit \( A_0 \), is expressed by the following equations with respect to Eqs. (6a) and (6b):

\[
\begin{align*}
\text{Eq. (7a):} & \quad f_0 = E_s \cdot f_1 \cdot A_0^* \\
\text{Eq. (7b):} & \quad f_0 = E_s \cdot \overline{f_1} \cdot A_0^*
\end{align*}
\]

Equations (7a) and (7b) mean that the signal processing circuit \( A_0 \) generates \( f_0 = E_s \cdot f_1 \) or \( f_0 = E_s \cdot \overline{f_1} \) only when it is normal (\( A_0^* = 1 \)) and always generates \( f_0 = 0 \) when it is faulty (\( A_0^* = 0 \)).

Now, the conditions for the signal processing circuit \( A_0 \) to generate \( f_0 = 0 \) when it is faulty are presented. Assume that the signal processing circuit \( A_0 \) is a NOT circuit (or arithmetic circuit represented by Eq. (7b)). When a break fault occurs in the input line \( a \), an \( f_0 = 1 \) error occurs despite \( f_1 = 1 \) (or \( f_1 = 0 \)). Namely, the output signal \( f_0 \) does not always accidentally become 0. This can be made more obvious if the signal processing circuit \( A_0 \) is divided into \( A_1 \) and \( A_2 \), where \( A_2 \) is a NOT circuit. In this case, the \( f_0 = 1 \) error occurs when a break fault occurs in any one of the lines \( a \) to \( c \). The signal processing circuit \( A_0 \) must not include any NOT operation, and its signal processing must be based on Eq. (7a). The input/output relation of Eq. (7a) is expressed by \( f_0 \equiv f_1 \overline{a} \) and is given in the truth table of Table 1 (\( f_1 > 0 \)).

Fail-safe signal processing does not allow any errors in signals which indicate safety. The output signal \( f_0 = 1 \) must be denoted by a high logic level as a signal indicating safety (\( f_0 = 0 \) does not indicate safety), and the input signal \( f_1 = 1 \) must be entered at a high logic level (high-energy state) as a signal indicating safety (\( f_1 = 0 \) does not indicate safety).

3.3 Method for generating slide position signals

The slide position signals \( P_1 \) to \( P_4 \) for defining the crank angles \( \theta_b \) to \( \theta_b \) in Fig. 2(a) have a safe side (logic 1), functionally defined as the binary signals described below. It is assumed that the slide positions where the signals \( P_1 \) to \( P_4 \) are produced are unchanged.

\( P_1 \): \( P_1 \) is a signal that provides an inspection criterion. Inspection is possible when \( P_1 \) is produced and not possible when \( P_1 \) is not produced. Safety is indicated by \( P_1 = 1 \), and the slide begins to operate under the condition \( P_1 = 1 \).

\( P_2 \): \( P_2 \) is a signal that provides a slide deceleration command and indicates the start of inspection at the top dead center. Since it means stopping of the slide between \( q_1 \) and \( q_1 \) and the permission for slide operation (safety) in the other sections, \( P_2 \) is not allowed to accidentally become 1.
$P_1$: Since it is safe on the up stroke and hazardous on the down stroke, the up stroke must be denoted by $P_1=1$. $P_1=0$ thus denotes the down stroke (hazard).

$P_2$: Since this is a signal that does not allow the run buttons to be pressed, $P_2$ must be logic 0 at the beginning of run button off-state confirmation, as described later. When $P_2=1$, the run button on-state signal can be accepted.

4. Generation of Operation Preparation Signals

This section describes a concrete method of sampling using fail-safe logic elements for overrun monitoring and run button off-state confirmation signals as the operation preparation signal $S_{sa}$ defined in section 3, in order to execute control without machine hazard errors.

4.1 Overrun monitoring

The brake performance of the mechanical press is confirmed by checking to see that the slide can stop within the specified range of the top dead center after the engagement of the brake. If this confirmation is carried out for each slide cycle, as shown in Fig. 2, a good result of inspection must be maintained until the next inspection. If the result of inspection is good in the operation preparation section from the crank angle $\theta$ to $\theta$, the slide starts to move with $S_{sa}=1$. This result is maintained as $S_{sa}=1$ on the down stroke and as $S_{sa}=1$ on the up stroke, and is reset by inspection in the operation preparation section. $S_{sa}=1$, $S_{sa}=1$, and $S_{sa}=1$ are the reasons why the good results of inspection indicate safety, and they assume logic 1 (high level of output state).

Figure 4 shows an example of an overrun monitoring sequence in the form of a time chart. $P_1$, $P_2$, and $P_3$ are the top dead center stop confirmation signal, top dead center stop signal, and up-stroke signal, respectively, described earlier, and indicate the corresponding movement of the slide in terms of the crank angle. $P_1=1$ indicates the operation preparation (inspection) section, $P_1=0$ indicates the start of inspection, and $P_1=1$ indicates the slide up-stroke section. The crank angle of 340° at which the top dead center stop confirmation signal $P_1$ is produced, is set to prevent the slide drive power from being prematurely interrupted as a result of overrun monitoring. If the slide drive power is interrupted too early, work in the next cycle is not allowed. The crank angle range of 340° to 15° is the window of inspection.

If the slide is stopped at the top dead center (crank angles of 340° to 15°), the permission signal for the slide to be lowered by depression of the run buttons ($T=1$) is stored as $Q_1=1$ by the self-holding function. When the slide reaches the top dead center after one safety cycle, this memory is reset by the top dead center stop signal $P_2$ ($P_2=0$ between the crank angles of 300° to 345° and is usually produced when the relevant cam switch is turned off).

The role of the overrun monitor is to confirm brake performance. This confirmation is positional confirmation after the rise of the slide and is made at the top dead center. If the result of this confirmation is good, there is no more need to interfere with the subsequent movement of the slide during the safety cycle (provided that the brake does not rapidly deteriorate). Once the slide position is confirmed, an operation permission signal must be generated before the next confirmation. The self-holding function is required for this purpose. If the slide stops in the range of $P_1=1$ in Fig. 4, for example, it can be started by the depression of the run buttons. When the slide stops beyond the crank angle of 15° ($P_1=0$) after it is started in the range of $P_1=1$, it cannot be restarted if the slide start condition depends only on $P_1=1$. Given the purpose of overrun monitoring, there is no reason to disable the slide from restarting. The result of brake performance confirmation must be held in the section of $P_1=0$ as the permission signal by the self-holding function. The operation permission signal $Q_2$ until the next confirmation of brake performance is represented as the logic sum of the output signal $Q_i$ of the self-holding function, up-stroke signal $P_1$, and top dead center stop confirmation signal $P_1$:

$$Q(t) = Q_i(t) \lor P(t) \lor P_1(t). \quad (8)$$

The self-holding function output signal $Q_i$ is given by

$$Q_1(t) = T(t) \cdot P_1R(t), \quad (9)$$

where $P_1R$ is a reset signal of the top dead center stop signal $P_1$. [ $(t)$ in Eqs. (8) and (9) is omitted hereafter.]

In Eq. (8), $Q_i$, $P_1$, and $P_1$ are produced at the specified positions as the slide moves through one safety cycle. Equation (8) provides a logic sum on the time axis. If the signals $Q_i$, $P_1$, and $P_1$ are taken to
be operating conditions for each cycle, \( Q_2 = 0 \) if any one of the signals \( Q_1, P_3, \) and \( P_1 \) is zero during the operating cycle. If the brake performs poorly and the slide stops beyond the crank angle of 15°, Eq. (8) means that \( P_1 = 0 \) and \( Q_2 = 0 \) are produced, which disallow the slide to be operated.

Figure 5 shows a concrete configuration of the overrun monitor circuit. The overrun monitor output signal given by Eq. (8) is produced as the operation permission signal. When any one of the signals \( Q_1, P_3, \) and \( P_1 \) becomes 0, \( Q_2 = 0 \) must be produced, and the self-holding condition must be entered as the reset signal into the self-holding function. In Fig. 5(a), \( M_x \) is a fail-safe self-holding circuit. (It produces a logic 0 output signal when it fails. The circuit elements described hereinafter are all assumed to have this characteristic.) The signal \( S_s \) of the start button is a self-holding circuit preset button pressed to start the operation of the mechanical press and turned on immediately after the power of the controller is turned on) is a trigger signal, and the top dead center stop confirmation signal \( P_1 \) is a reset signal. The output signal \( Q_{so} \) of the self-holding circuit \( M_x \) causes the run buttons \( T \) to allow the slide to move, and the slide moves with respect to the top dead center stop confirmation signal \( P_1 \), as shown in the time chart of Fig. 5(b). The run button signal is not directly used as the trigger signal because, as expressed by Eq. (9), the self-held result of overrun monitoring must be reset by the top dead center stop signal for each cycle of slide operation, and permission for the next cycle of slide operation to be repeated must be given by Eq. (8) or \( (T \cdot P_2 R) \lor P_3 \lor P_1 \).

Figure 5(c) illustrates an overrun monitor circuit that holds the start button signal \( S_s = 1 \) according to Eq. (8). \( M_x \) is a self-holding circuit that uses the run button signal \( T = 1 \) as the trigger signal and the top dead center stop signal \( P_1 \) as the reset signal. Its output signal corresponds to Eq. (9). The logic circuit \( RM \) performs logic operation on Eq. (8) and produces the output signal \( Q_s \). The self-holding circuit \( M_x \) starting the slide produces the operation permission signal \( Q_s \) by taking the output signal \( Q_s \) as a reset signal. The operation permission signal \( Q_{so} = 1 \) is fed back to the AND gate \( R4 \) and is held, unless the slide overruns the top dead center (or stops after the top dead center stop confirmation signal), according to the result of the logic operation by Eq. (8).

4.2 Confirmation of run button off state

Figure 6 shows the run button off-state confirmation circuit. The off-state of the run buttons is denoted by the binary logic variable \( T' = 1 \) when the run buttons are turned off. In reality, \( T' \) can be equated with \( -T \). Since the usual NOT operation (→) cannot be used in fail-safe signal processing, as described in section 3.2, however, the off state of the run buttons is denoted by the prime "′".

Figure 6(a) illustrates the principle of confirming that the run buttons are turned off, or \( T' = 1 \). When the run buttons are turned off \( (T = 1) \) after the generation of the signal \( P_1 (=1) \), the run button off-state confirmation signal \( Q_{so} = 1 \) is produced in the self-holding circuit \( MR \), as shown in the time chart of Fig. 6(b). As the slide rises from the bottom dead center, this output signal is self-held until the antire-
peat signal $P_1$ turns off ($P_1=0$).

Consider the case in which the circuit of Fig. 6(a) is used in the control system of the mechanical press. Since the run buttons are always turned off prior to the start of press operation, $Q_t=1$ is produced as soon as the power to the press is turned on. The press system is started with the start button, as shown in Fig. 5. In addition to this start condition, the start signal $S_t$ must be produced before $Q_t=1$ can be generated.

Figure 6(c) shows the true method of producing the start signal using the circuit of Fig. 5(a). The output signal $Q_s$ of the self-holding circuit $M_s$ is produced when the start button is turned on ($S_t=1$). When the start button is turned off ($S_t=1$), the output signal $Q_s$ is converted and generated as the true start signal $Q_{st}=1$. When the start button is released to the off-state, the true start signal $Q_{st}=1$ is produced, based on the confirmation that the start button can be reset (for example, the start button does not collapse into a false on state due to breakage of the spring).

Figure 6(d) represents the method of confirming the off-state of the run buttons using the antirepeat signal $P_t$. The operation preparation signal $S_{op}$ is produced as the logic product of the overrun monitor output signal $Q_s$ and the antirepeat signal $P_t$. When the slide exceeds the crank angle of $15^\circ$ (range of $P_1=1$), $P_1$ becomes 0, and the start signal disappears or $Q_{st}$ becomes 0 in Fig. 6(c). The overrun monitor signal $Q_s$ [Fig. 5(c)] is used in place of the start signal $Q_{st}$ [Fig. 6(c)]. The logic product of the overrun monitor signal $Q_s$, antirepeat signal $P_t$, and start button off-state signal $S_t$ is used as the reset signal of the self-holding circuit $M_R$. The circuit of Fig. 6(d) thus has the functions illustrated in Figs. 6(a) and (c), and the logic product of the operation permission signal based on overrun monitoring and the operation permission signal based on run button off-state confirmation can be used as operation preparation signals. The run button signals $T$ and $T'$ and the start button signals $S_t$ and $S_{i1}$ are dual signals that do not become 1 at the same time ($T \cdot T'=0$, $S_t \cdot S_{i1}=0$).

5. Conclusions

The mechanical press work system is a man-machine system in which both the machine and human operator may make errors. The method of constructing a machine control system that assures safety if the operator does not take any hazardous action intentionally is presented. There is the need for such an interlock that allows the slide to move down when there is no part of the operator's body on the bolster and when the machine control system has no error. As an interlock to prevent any errors in the machine control system, an operation preparation section is provided where the slide changes from the up stroke to the down stroke, and the slide is allowed to move down according to the result of brake performance inspection (overrun monitoring) in the operation preparation section. The confirmation of brake performance calls for confirmation of the interruption of the slide drive power as well as for the slide stop command and stop confirmation signal. In reality, an interlock to confirm the off-state of the run buttons should be added.

The two interlocks of the machine system must be realized by a fail-safe configuration. Four slide position signals are defined to construct the necessary interlocks, and the characteristics required of the four signals are presented. As a circuit comprising the two interlocks in a fail-safe configuration, a self-holding circuit is built from fail-safe logic elements by taking the press start signal as a seed. The signal to permit the slide to move down can be produced if the output signal of the self-holding circuit is given as the reset signal.

References


