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Automatic Plate Warehouse Crane

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Abstract:

The selection control of the number of plates to be lifted together by a lifting magnet crane and the operation control of multiple lifting magnet cranes are necessary and indispensable key techniques for the automation of a plate product warehouse. At the plate mill product warehouses of Kimitsu and Oita Works, we tackled the development of these elementary techniques and the enhancement of lifted plate quantity selection accuracy and crane operation efficiency, and succeeded in the fully automatic operation of the lifting magnet cranes in the large plate product warehouses.

1. Introduction

The plate production process that forms the core of a plate mill was automated to an advanced degree by introducing various measuring instruments and developing rolling control techniques. With no techniques developed to substitute for skilled crane operators, the plate product warehouse was left out of this rationalization trend.

The warehousing of plate products mainly consists of the repeated selection of plates to be lifted with dedicated lifting magnet cranes. This lift selection calls for the skills of crane operators. Since any mistakes made in the warehouse at the final stage of the plate mill directly lead to wrong shipments, the plates to be lifted must be selected with high accuracy and with high efficiency to make effective use of the limited storage area. The full automation of these plate handling tasks was considered to be extremely difficult. After the development of necessary technology for the full automation of plate lift selection and lifting magnet crane operation, Nippon Steel succeeded in the world's first unattended operation of large plate product warehouses in September 1992.

This article describes the techniques developed for controlling the number of plates to be handled by lifting magnet cranes and automatically controlling the operation of the lifting magnet cranes as bases for the unattended operation of the plate product warehouses, and it presents the application results of these techniques.

2. Outline of Warehousing Tasks and Main Development Issues

The layout of the plate mill at Oita Works is shown in **Fig. 1**, and the equipment outline of the plate product warehouse at the Oita plate mill is shown in **Fig. 2**. The plate product warehouse occupies the northern half of bay 3, and bays 4 and 5. Bay 4 ware-

*1 Oita Works
*2 Kimitsu Works

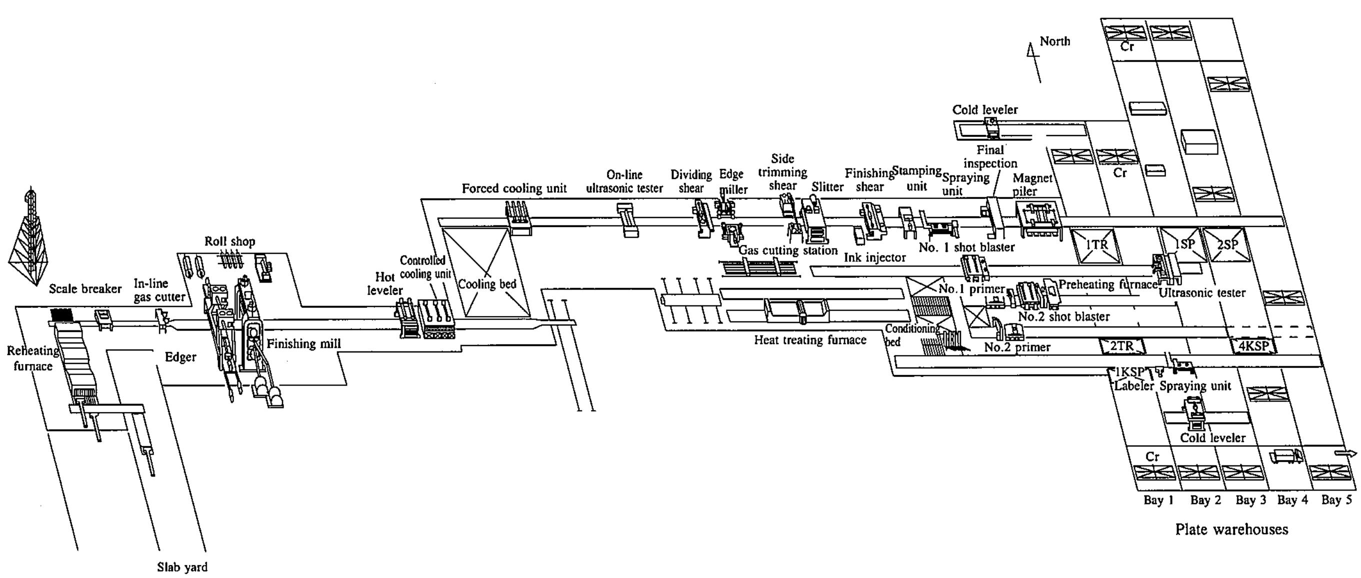


Fig. 1 Layout of Oita plate mill

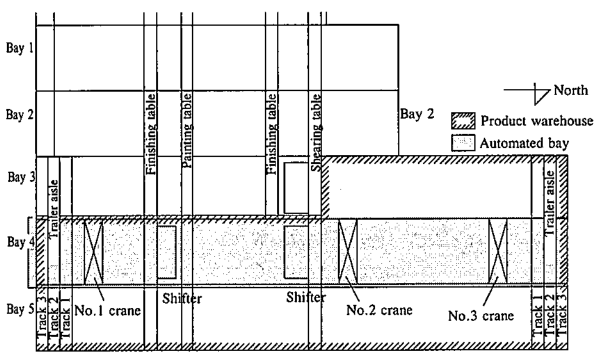


Fig. 2 Equipment outline of plate warehouse at Oita plate mill

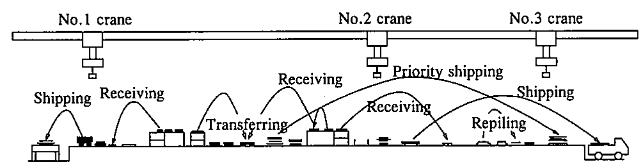


Fig. 3 Outline of plate warehousing tasks

house was automated in September 1992 and now handles plate products, measuring 8 to 60 mm in thickness, 1,000 to 3,300 mm in width, and 3,000 to 14,500 mm in length. The main tasks performed in the warehouse are shown in **Fig. 3**. Plates are received from shearing and finishing lines, loaded on carrier pallets and trailers standing by in south and north aisles, and repiled for specific destinations. Bay 4 warehouse has three cranes installed on the same runway rails for performing these jobs. The automatic operation control of the three lifting magnet cranes called for the development of two main technologies as described below.

(1) Control technology for selecting number of plates to be automatically lifted together

1) Technique for selecting the number of plates to be lifted together, capable of selecting the specified number of plates to be lifted on the first try from among plate groups of various sizes with a high success rate and reliability.

2) Technique for judging the number of plates to be lifted together, capable of accurately checking the surplus or shortage of plates and the state of plates in each lift, and performing the control of plates as handled with cranes with reliability of 100% from reception into the warehouse to shipment from the warehouse, from the standpoint of preventing wrong plates being shipped to wrong customers.

(2) Technology for automatically controlling operation of multiple lifting magnet cranes

1) High-efficiency operation control technique for reducing the frequency of mutual interference between the lifting magnet cranes in their operation process and for completing each cycle of hoisting, transporting and lowering in a minimum of time.

The main development issues and developed techniques are outlined in **Table 1**.

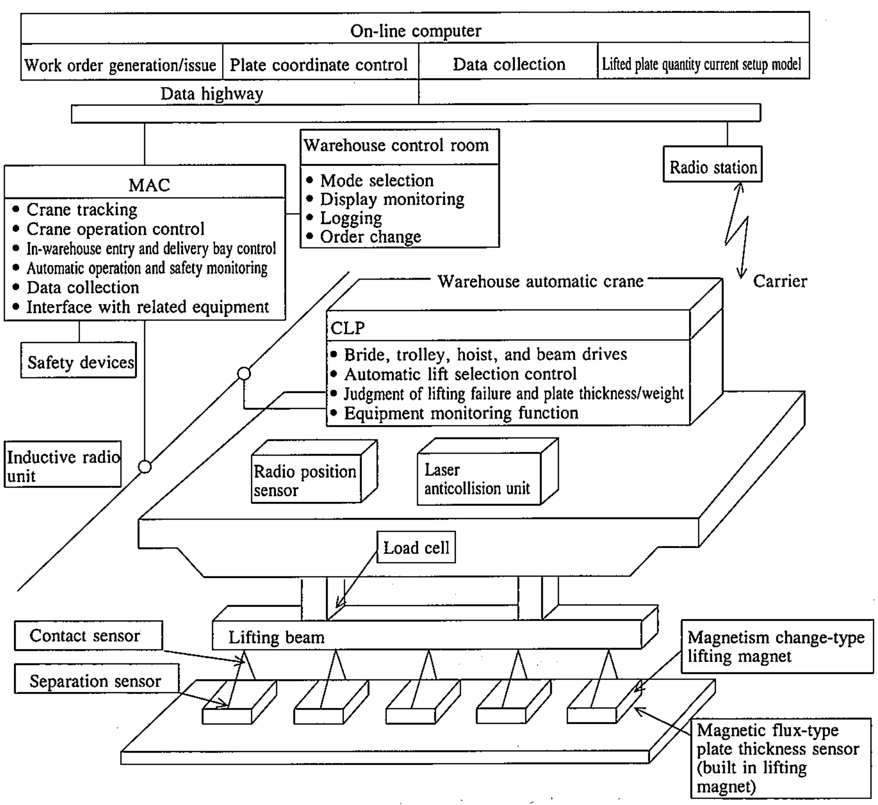
3. Automatic Control System for Plate Warehouse Cranes

3.1 Configuration of automatic crane system

The configuration of the automatic crane operation system built by applying the developed techniques is shown in **Fig. 4**. The system mainly consists of an on-line computer that generates work orders, controls plate coordinates, and calculates lifted plate quantity selection current set points; a multiple automatic crane controller (MAC) that controls the operation of the cranes; and three crane local processors (CLPs) that perform automatic lift selection control and drive control (hoist, bridge and trolley). The on-line computer and MAC are connected through modems, and the MAC and CLPs are connected by inductive radio.

Table 1 Main development issues and developed technologies

Development issue		Outline of developed technology	Developed apparatus
1. Automatic lift selection control technology	(1) Lifting magnet exciting current control	• Current setting control technique (attractive force characteristic model) that applies necessary and sufficient attractive force to plates when lift is selected. • Instantaneous current compensation control technique that compensates for decrease in attractive force due to deflection of plates when lifted and variation in attractive force due to level difference between floor and lifting magnet, and improves lift selection performance	• Separation sensor that determines instant when plates are lifted
	(2) Lift plate quantity judgment	• Technique that determines number of plates in each lift and state of each lift with magnetic flux-type plate thickness sensor built in lifting magnet and from lifting load	• Magnetic flux-type plate thickness sensor built in lifting magnet
	(3) Retry control	• Technique that removes excessive plate or plates and re-hoists insufficient plate or plates as measure against excess or lack of plates lifted	
2. Technology for automatic operation control of multiple cranes	(1) Work order creation system	• Work order issuing system that introduces function to evaluate adequacy of work orders and avoids operating rate deviation and mutual interference	
	(2) Operation control system	• Operation control system that allows cranes to be operated with maximum efficiency by considering priority of specific tasks (receiving, shipping, repiling) and time loss due to mutual interference of cranes	
	(3) Simultaneous three-axis drive control system	• Crane drive control system that determines shortest route from start point (hoisting) to end point (lowering), and simultaneously operates hoist, bridge, and trolley drives	



Equipment specifications of automatic cranes

Item		No. 1/No. 3 cranes	No. 2 crane
Rated lifting load		20 t×1 beam	15 t×2 beam
Span		32.6m	32.6m
Lifting height		4.0m	4.0m
Beam expansion range		5.2m-11.5m	5.2m-11.5m
Number of lifting magnets		5/beam	4/beam
Speed	Bridge motion	120m/s	120m/s
	Trolley motion	40m/s	40m/s
	Hoist motion	16m/s	10m/s
	Beam motion	63m/s	63m/s

Fig. 4 Configuration of automatic crane operation system

3.2 Technology for automatically selecting number of plates to be lifted

With the conventional method of selecting the number of plates to be lifted together, the crane operator determined the number of lifting magnets to be used and the value of current to be applied to the lifting magnets from the size and number of plates to be lifted together. Whether or not the plates were lifted in the specified quantity was checked with a plate weight measuring instrument (load cell). When plates of low weight were mixed in a lift, making it difficult to check the number of plates in the lift with the load cell, the crane operator visually verified the number of plates in the lift. This method was inefficient. The development of the technology for controlling the number of plates to be lifted together was carried out as divided into three elementary techniques shown in **Table 2**: (1) control of lifting magnet exciting current to ensure a high success rate at the first try; (2) plate quantity judgment to check the number and state of plates in each lift; and (3) retry control as a measure against a failure to lift on the first attempt[1].

3.2.1 Lifting magnet exciting current control

The lifting magnet attractive force characteristic model as a key to the selection of the number of plates to be lifted together was built by measuring the relationship between the electric current and the attractive force of actual lifting magnets of the polarity conversion type[2,3] while changing the thickness and number of plates to be lifted off-line and by formulating the measured data. **Fig. 5** shows the principle of lifted plate quantity selection and typical attractive force characteristic measurements. The following are two of the findings derived from the measurements:

1) If the thickness t_n of the n-th plate is the same and if the total thickness and number of n-1 plates are the same, the constitutive differences of individual plate thicknesses and widths have no effect.

2) If the n-1 plates are the same in total thickness but different in number, a small increase in the air gap between the plates reduces the attractive force (see **Fig. 6**).

According to these findings, the attractive force data were arranged into a table of numerical values by the number n of plates to be lifted, the total thickness t_{n-1} of n-1 plates, the thickness t_n of the n-th plate, and the polarity of the lifting magnets. When the lift contains a plate narrower than the lifting magnets, the current value determined from the attractive force table is compensated for the position of the narrow plate.

During the transient period of lifting the plates, the attractive force varies with the level difference of the floor surface or lifting magnets and the deflection of the plates. Each crane has the lifting beam fitted with four to five lifting magnets. When a plate is lifted, the lifting magnets do not always assume the same level due to the deflection of the lifting beam, among other things. **Fig. 7** shows the results obtained when a level plate was placed on the floor, the #1 to #3 lifting magnets were set at such intervals as to ensure a

Table 2 Elementary techniques comprising automatic lift selection control system

Elementary technique			Development point		
(1) Lifting magnet exciting current control	Attractive force characteristic model		High lift selection performance	Setup of base current from lifting magnet attractive force-exciting current characteristics	
	Instantaneous current compensation control	Deflection compensation current control		Attractive force variation compensation	Compensation of variation in attractive force with plate deflection
		Lifting magnet current control			Compensation of variation in attractive force characteristic with level difference
		Separation sensor			Lifting magnet separation sequence detection
	Polarity conversion-type lifting magnet			Improvement in lifting magnet lift selection performance (NSC jointly with Sumitomo Heavy Industries)	
(2) Retry control	Current resetting control			Insufficient lift: Resetting of current for next lift	
	Current gradual decrease control (disengagement control)			Excessive lift: Gradual decrease in current and removal of excessive plate or plates	
(3) Lift quantity judgment	Magnetic flux-type plate thickness sensor		Improvement in reliability by double check with magnetic flux-type plate thickness sensor and load cell		

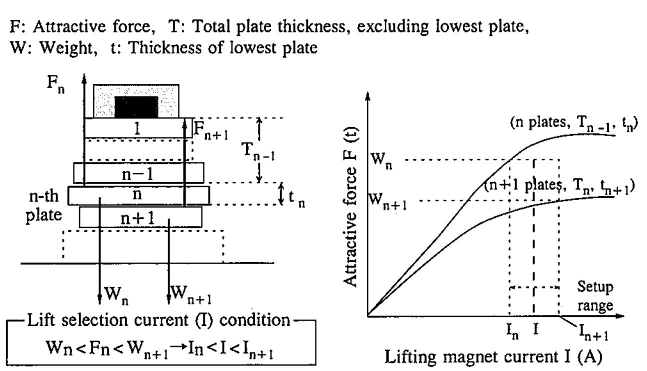


Fig. 5 Principle of selecting number of plates to be lifted together and attractive force characteristic diagram

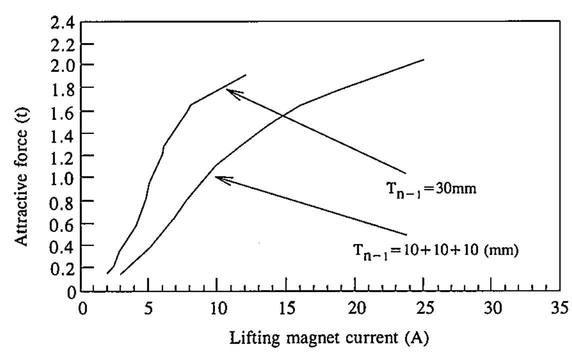


Fig. 6 Attractive force characteristic diagram (total thickness of up to n–1 plates is equal, but number of plates is different)

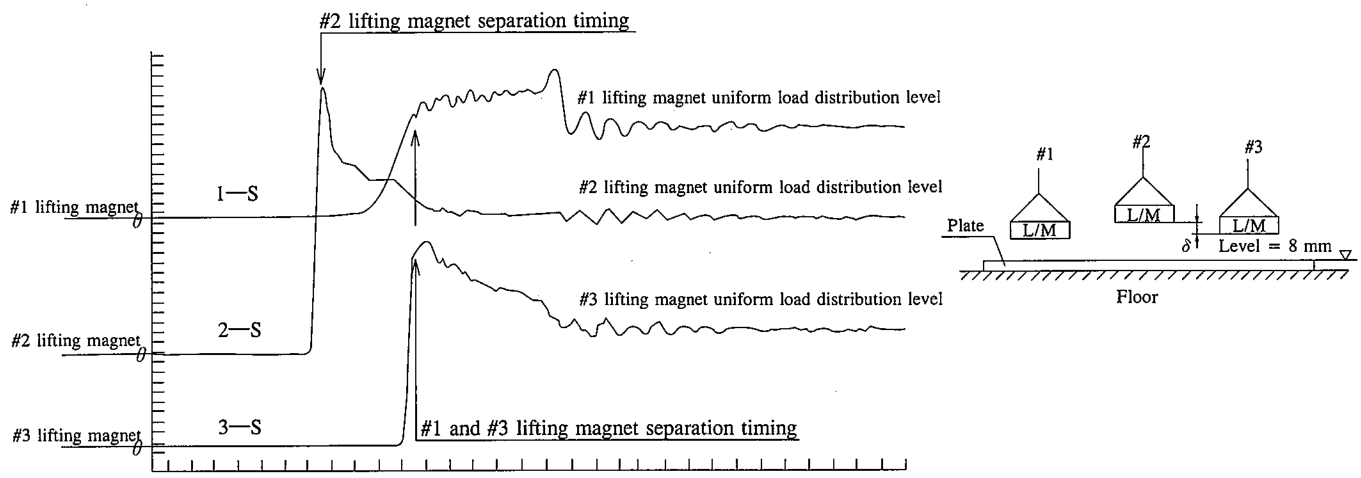


Fig. 7 Change in load in separation sequence when lifting magnets were set at different levels

uniform load distribution among themselves, and the #2 lifting magnet was located 8 mm above the #1 and #3 lifting magnets. The #2 lifting magnet was subjected to a greater load than its share of the uniformly distributed load as soon as it separated from the floor surface. As the #1 and #3 lifting magnets then moved away from the floor surface, the load carried by the #2 lifting magnet gradually approached its share of the uniformly distributed load.

Fig. 8 shows the deflection of an 8-mm thick plate lifted and the current set to take care of the air gap produced by the deflection of the plate. When the plate is deflected to a maximum of 500 mm, the setup current magnification is about 5×, meaning that a considerable amount of compensation is required. An instantaneous current compensation control technique was developed to cope with disturbances that may occur during the transient period of plate lifting. That is, the timing when the plate separates from the floor surface is sensed for individual lifting magnets, and the current set from the attractive force table is compensated for the difference in this timing between the lifting magnets.

The instantaneous current compensation control technique is outlined in **Fig. 9**. The deflection compensation current and the separation sequence compensation current are added to the current set from the attractive force table and are controlled for individual lifting magnets. The timing of the plate separation from the floor surface is detected by the separation sensor installed in each lifting magnet. The compensation current is added in the separation sequence. The deflection compensation current is strictly predicted by calculating with high accuracy the plate deflection in the width and length directions according to plate deflection theory.

3.2.2 Lifted plate quantity judgment and retry control functions

The lifted plate quantity judgment and retry control methods are outlined in **Fig. 10**. The number of plates lifted together are double checked by a conventional load cell and a magnetic flux-type plate thickness sensor[3] built into each lifting magnet to improve reliability.

Fig. 11 shows examples of plate thickness sensing characteristics of the magnetic flux-type plate thickness sensor. The sensing errors are ±2 mm and are small enough to discriminate a minimum plate thickness of 8 mm. The plates are judged to be lifted normally when they meet both the weight and thickness checks. The lift is judged to be insufficient when either the total weight or thickness check is smaller than actual, to be excessive when either the weight or thickness check is larger than actual, and to be impossible when

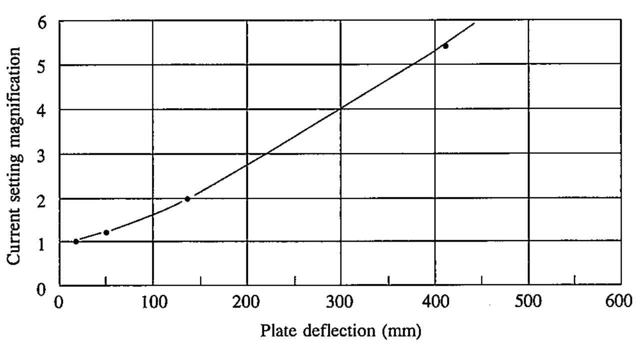
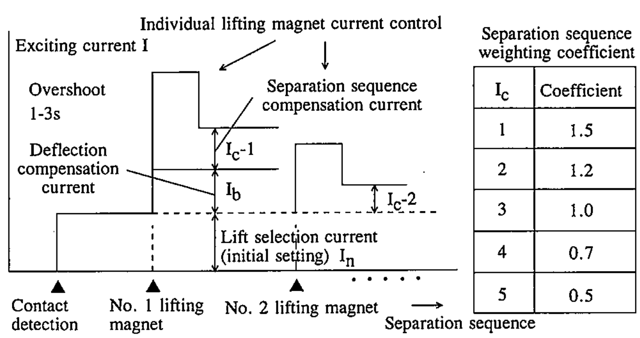


Fig. 8 Plate deflection and current setting magnification



I_c	Coefficient
1	1.5
2	1.2
3	1.0
4	0.7
5	0.5

Fig. 9 Instantaneous current compensation control

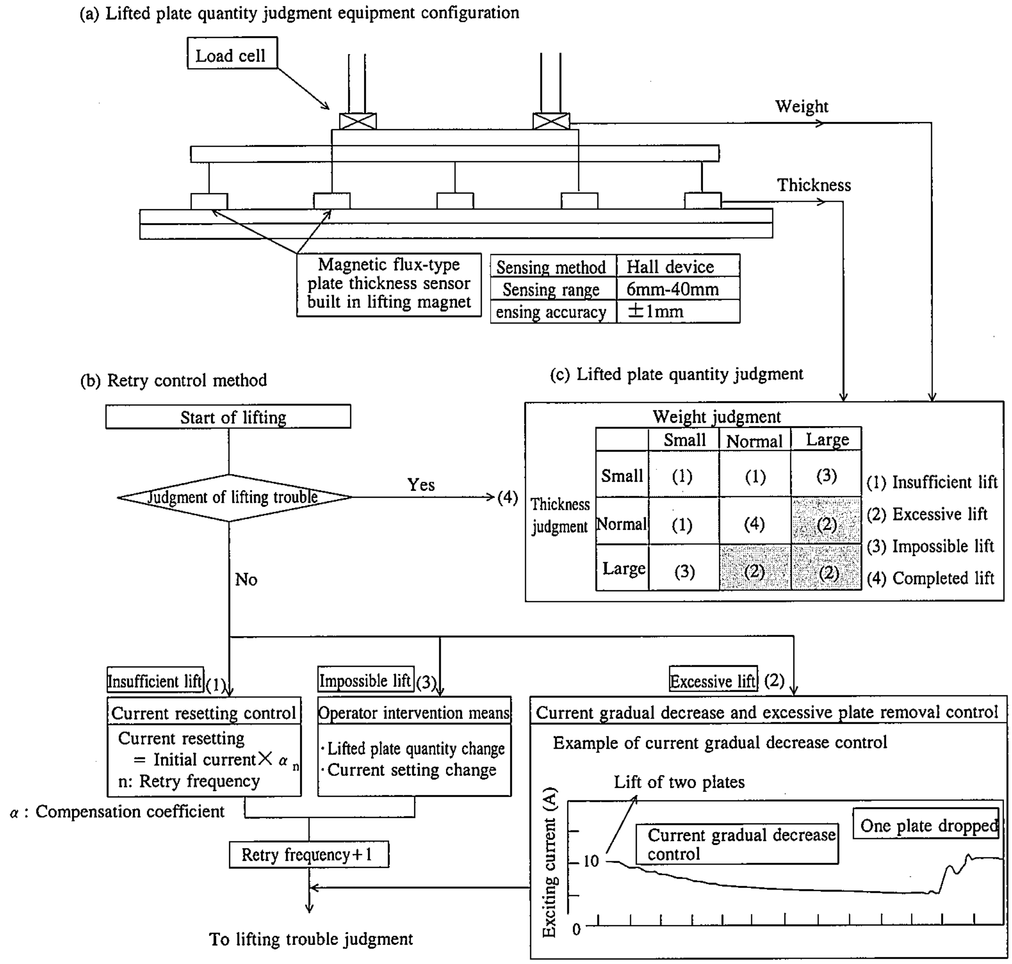


Fig. 10 Lifted plate quantity judgment and retry control

the weight and thickness are both larger than actual. When the lift is judged to be insufficient, it is first lowered and then hoisted again with an increased exciting current set point. When the lift is judged to be excessive, it is stopped suspended with a minimum of vibration, and the excessive plate is dropped by gradually reducing the exciting current. When the control to drop the excessive plate is relatively easy to effect according to the plate combination concerned, the current command to the lifting magnets is instantaneously weakened as shown in **Fig. 11**(b). When this instantaneous current cut control is difficult to make, the magnetic flux command to the lifting magnets is gradually weakened. There are various lifting troubles as shown in **Fig. 12**. When a lifting trouble is caused, its disposal is left to the discretion of the crane monitoring operator without activating the retry function.

Table 3 shows the results of these lifting magnet exciting current control techniques as tested with many plate lifts. The success rate of first lift selection is more than 90% and nearly 100% when retries are included. It was demonstrated that lift selectivity is practically high enough.

3.3 Technology for automatically controlling operation of multiple cranes

To operate multiple cranes with high accuracy, it is essential to minimize the cycle time after the issue of a work order. When the same order was given to a single crane, the automatic cycle time was almost the same as the manual cycle time or slightly shorter than the manual cycle time. When multiple cranes were operated at the same time, the automatic cycle time was measured to be 294 s/order and was about 1.3 times longer than the manual cycle time of 225 s/order. This difference was the difference in intellectual judgment between the computers from the on-line computer to the CLPs and the human operators. It was thus necessary to develop the three aforementioned techniques: (1) optimum work order generation system; (2) high-efficiency operation control system; and (3) automatic operation control system (simultaneous three-axis or host, bridge and trolley drive control).

3.3.1 Optimum work order generation system

Conventional crane work orders were generated according to task priority and based on a table of approximately assigned crane travel ranges. When a crane interference resulted from an issued order, its correction was left to the discretion of the operators. Besides the conventional job priority, the new evaluation criteria, or degrees of conformance, concentration and interference, were established. Work orders were generated by functional equations that comprehensively evaluate these values[4]. The conformance, concentration, and interference degrees are briefly discussed below.

(1) Conformance degree: The conformance degree is a criterion for evaluating the conformance of the travel range specified by a work order and the movable range determined in positional relation to the crane. As shown in **Fig. 13** and **Table 4**, the warehouse is divided into eight zones on the basis of the equipment arrangement (such as tables and shipping zones), and a table is prepared of crane mobility priority degree with respect to work orders by zone (from-positions to to-positions). The values of the conformance degree table are determined based on the experience of skilled operators. The greater the value of a crane, the easier the crane is to be selected.

(2) Concentration degree: If the conformance degree alone is used, jobs may be concentrated on a particular crane. The concen-

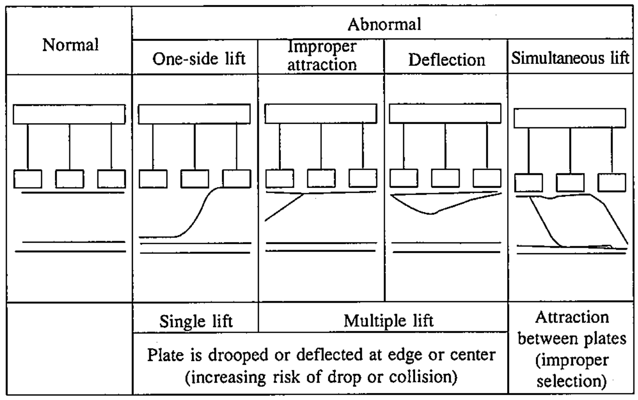


Fig. 12 Lifting troubles

Table 3 Automatic lift selection success rate

Initially successful lifts B	6,496
Retries C	554
Insufficient lifts	81
Excessive lifts	473
Successful retries D	551
Processed lifts A	7,051
Initial lift success rate B/A (%)	92.1
Retry success rate D/C (%)	99.5
Total selection success rate (B+D)/A (%)	99.96

Breakdown of initial lift success rates in October and November, 1992

		Distribution (%)	Success rate (%)
Quantity of plates lifted per time	1	39.5	100
	2	32.7	91
	3	16.9	83
	4	8.4	77
	5	3.4	71
Total		100	92.1

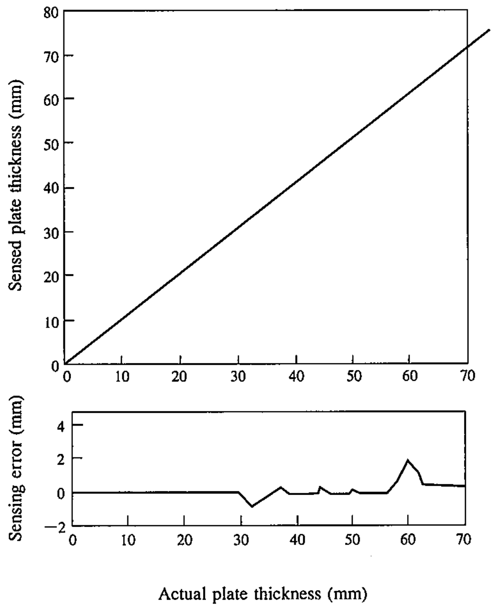


Fig. 11(a) Examples of plate thickness sensing characteristics

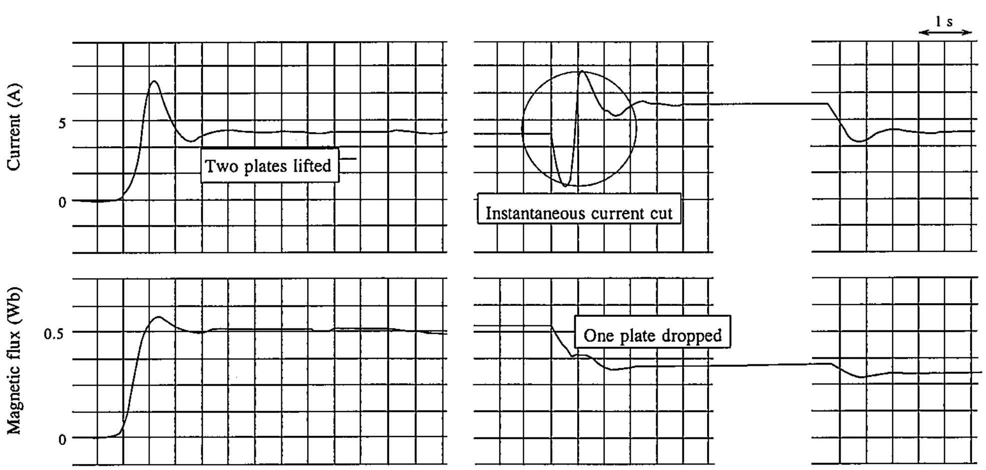


Fig. 11(b) Instantaneous current cut control

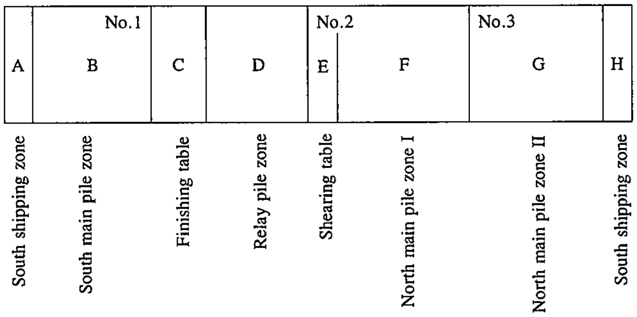


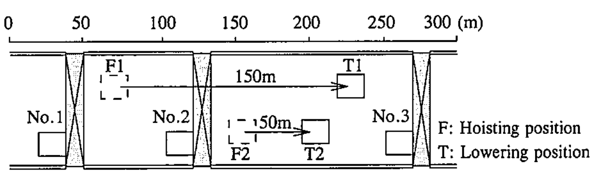
Fig. 13 Division of warehouse into zones

Table 4 Conformance degree table (excerpted)

From	A			B			C			......	H		
To	No.1	No.2	No.3	No.1	No.2	No.3	No.1	No.2	No.3	......	No.1	No.2	No.3
A	64	1	0	64	4	0	40	3	0	......	0	1	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	⋮	⋮
F	24	4	0	24	15	6	15	32	13	......	0	4	48
G	16	3	0	16	12	7	10	24	21	......	0	3	56
H	0	1	0	0	4	8	0	8	24		0	1	64

tration degree was thus introduced as another criterion. The concentration degree represents the frequency of priority jobs and the frequency of priority crane operation orders. The greater the value of a crane, the more the jobs are concentrated on the crane.

(3) Interference degree: The interference degree predicts the amount of interference between an order already issued and an order to be issued, thereby preventing serious interference. Examples are shown in **Fig. 14** and **Table 5**. The interference degree is quantitatively evaluated as calculated from the weights of four interference distances, or the interference distance



Examples of interference between Nos. 1 and 2 cranes

	Interference combination	Interference map (F1, F2, T2, T1)	Interference distance	Remarks
A	F1−F2		0	Nos. 1 and 2 cranes can work independently
B	F1−T2		0	Nos. 1 and 2 cranes can work independently
C	T1−F2		50m	No. 1 crane must stand by
D	T1−T2	Interference region	25m	No. 2 crane must move back

Interference degree = (FF+TT+(TF+FT)× α) ×N

α : Adjustment coefficient (weighting interference between from-position and to-position)

N : Interference state coefficient (representing severity of interference; N = 2 for above example)

Fig. 14 Examples of interference degree

Table 5 Interference state coefficient list (for Nos. 1 and 2 cranes)

N		Example of interference pattern	Interference state
0	No.1	T ⟵ F	No interference
	No.2	F ⟶ T	
1	No.1	T ⟵ F	Small
	No.2	F ⟶ T	
2	No.1	F ⟶ T	Medium
	No.2	F ⟶ T	
3	No.1	T ⟵ F	Large
	No.2	F ⟶ T	
4	No.1	F ⟶ T	All interference
	No.2	T ⟵ F	

N: Interference state coefficient

There are 14 interference patterns in total.

Interference degree is quantified by covering all interferences that may occur as cranes are operated.

From1From2 between the job start positions, the interference distance To1To2 between the job end positions, and the interference distance between the job start (or stop) position and the job end (or start) position From1To2 (or To1From2), and from the weights of interference conditions. The interference degree increases with increasing interference distance and interference condition.

The evaluation function is calculated from these criteria as given by Eq. (1). An order is generated when the calculated value of the evaluation function exceeds the evaluation criterion value.

Evaluation function: a×Priority degree + b×Conformance degree/ (c × Concentration degree) −d×Interference degree ≥ Evaluation criterion value ······(1)

where a to d are adjustment coefficients.

3.3.2 High-efficiency operation control system

The determination of a priority crane after the issue of an order is a kind of planning problem. The search method, a representative solution method, was used to solve the problem with the MAC. An excessive computing load made it difficult to apply the search method to the problem of priority crane determination. Instead, a simpler evaluation function method was employed in the same way as described for the work order generation system.

The evaluation function consists of three parameters, or (1) priority degree (w) of a job, (2) elapsed time (T) after the reception of an order, and (3) travel distance (L) to a target, as given by Eq. (2).

Evaluation function: J = e×w + f×T + g×L ······(2)

where e to g are adjustment coefficients. The adjustment coefficient e for the priority degree of jobs is set so that urgent jobs alone are given top priority.

3.3.3 Simultaneous three-axis hoist, bridge and trolley drive control

The simultaneous three-axis drive control method is schematically illustrated in **Fig. 15**. It is not described in detail here. The shortest route to minimize the transfer time from the start point to the end point of each job was calculated on-line, and the selected crane simultaneously performed the hoist, bridge, and trolley motions as required to shorten the plate handling time[5].

Fig. 16 shows the results obtained when the automatic operation control system was tested with many plate lifts. The operation

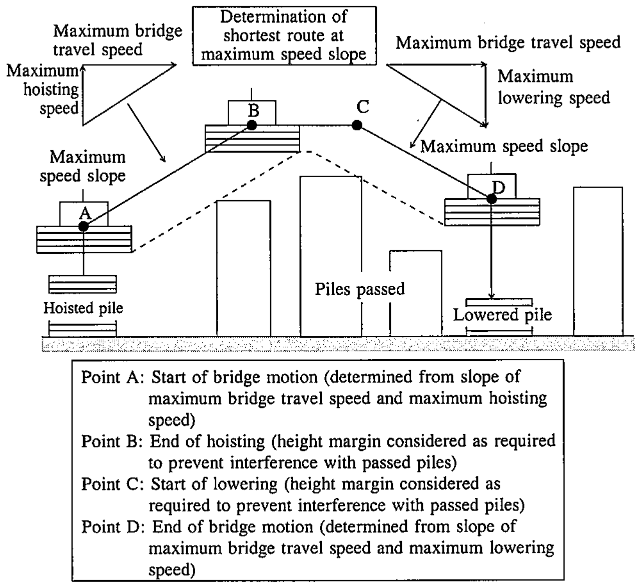


Fig. 15 Simultaneous three-axis drive control

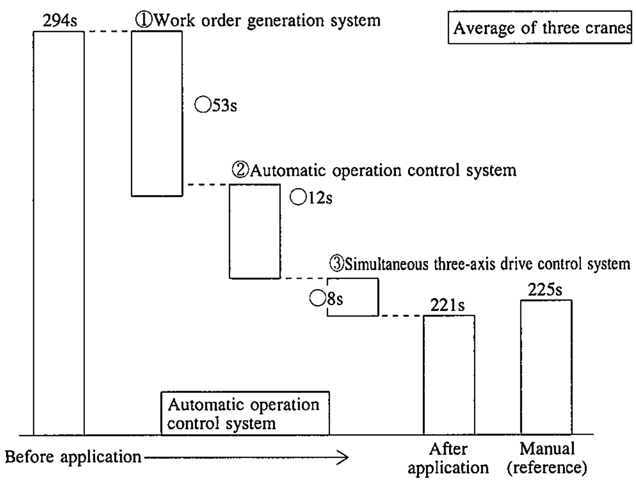


Fig. 16 Change in cycle time (time required to complete one job)

control of multiple cranes was traditionally considered to require an advanced intellectual judgment system like an artificial intelligence system. The simple evaluation function method presented here succeeded in operating multiple cranes with efficiency equal to or greater than that demonstrated by skilled operators.

4. Safety Measures

Besides the main techniques developed as discussed above, various unauthorized entry sensors and alarms were installed throughout the warehouse to prevent the wrong entry of operators into the warehouse during automatic crane operation from the standpoints of personnel and equipment protection. Mutual positions were recognized between the cranes. At the same time, the cranes were fitted with emergency stop functions to prevent their collision. The safety measures implemented in the warehouse are shown in **Fig. 17**.

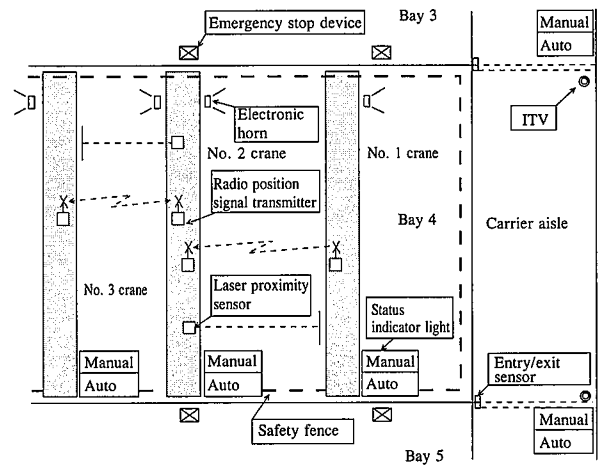


Fig. 17 Arrangement of safety devices in automatic warehouse

5. Conclusions

The following technologies were developed for the automatic operation of lifting magnet cranes: (1) technology for automatically selecting the quantity of plates to be lifted together and (2) technology for automatically controlling the operation of multiple cranes.

These technologies improved the accuracy of selecting the quantity of plates to be lifted together and enhanced the efficiency of operating cranes to a level comparable to that of human operators. They were instrumental in the successful automatic operation of large plate warehouses at both Oita and Kimitsu Works[6].

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