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AUTOMATIC CONTROL SYSTEMS FOR CONSTRUCTION MACHINERY

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ABSTRACT

Automatic control systems for construction machinery have been developed, which control the motion of attachments. The purpose of these systems is to simplify such difficult operations as level crowding of a hydraulic excavator and level luffing of a crawler crane. The control systems consist of a microcomputer-based controller, sensors and hydraulic actuators. The nonlinear characteristics of hydraulic actuators and low rigidity of structure of construction machinery make it difficult to achieve high control accuracy and high stability performance. A control algorithm was developed to solve the problem for these systems and the validity of the algorithm has been verified by operating tests. The control algorithm is the combination of feedback control, feedforward control, nonlinear compensation and gain modification.

INTRODUCTION

Operations using construction machinery, for example level crowding of a hydraulic shovel and level luffing of a crawler crane, require a high level of skill, and cause considerable fatigue even in skilled operators, because more than two levers must be operated simultaneously and adjusted well in such operations. At the same time, the number of skilled operators is small. Such a situation requires construction machinery which can be operated easily by any person.

Therefore automatic control systems for construction machinery which control motion of attachments have been developed. The automatic control system for a hydraulic shovel allows level crowding and horizontal bucket lifting with one-lever operation. Using the level luffing control system for crawler cranes, an operator can safely move suspended loads level at elevated spots or on sites where visual operation is impossible.

In this paper are described the details of the control algorithm and the results of its application.

1. THE FUNCTIONS OF THE CONTROL SYSTEMS

1.1 The control system for a hydraulic excavator

1.1.1 Level crowding

When the arm is pushed forward by manual operation, the boom is automatically controlled to hold the arm end height constant. The motion of the attachments is shown in Fig. 1.

1.1.2 Horizontal bucket lifting and automatic return

When the boom is raised by manual operation, the bucket is automatically controlled to hold the bucket angle to the ground constant.
The angles of the boom, the arm and the bucket are put into the memory at the attachment position to be memorized. When this function is operating, the attachments are automatically moved to the memorized position.

1.2 The control system for a crawler crane

1.2.1 Level luffing

As shown in Fig.2, in crawler cranes, the suspended load is transferred by driving a boom drum and a hoisting drum with hydraulic motors. In this control system, when an operator raises or lowers a boom, a microcomputer controls a hoisting drum to keep the suspended load height (h in Fig.2) constant.

2. SYSTEM COMPONENTS

As shown in Fig.3, these control systems consist of sensors, a control panel, a microcomputor-based controller and a hydraulic system. The sensors used in the systems are shown in Table 1. The specifications of the controllers are shown in Table 2.
The features in the control system common to both an excavator and a crawler crane are as follows.

2.1 Use of electromagnetic proportional reducing valves

During manual operation, the pilot pressure of the hydraulic system is controlled by operation of the levers. During automatic operation, electromagnetic proportional reducing valves control the pilot pressure. The main control valves and the main pipes of the hydraulic system need not be modified for automatic control. Therefore the control systems can easily be added as an option to an ordinary machine. An electromagnetic proportional reducing valve costs less and resists oil contamination of oil better than a servo valve.

2.2 Detection of the lever condition for feedforward control

In these systems, one attachment is operated manually while the others are operated automatically. Therefore the manual operation is disturbance for the control system. In order to reduce control errors, the system provides for feedforward control based on detection of the manual operation. The controllers detect the progress of manual operation by focusing the lever position.

2.3 Detection of the lever condition for manual priority function

When this function is used, the lever of the usually automatic attachment is operated manually, which interrupts the automatic control. This is useful in the case of a sudden change in the desired control value, for example, in order to avoid an obstacle.

3. CONTROL ALGORITHM

In this section are described the control algorithms for the level crowding of an excavator and for that of the level luffing of a crawler

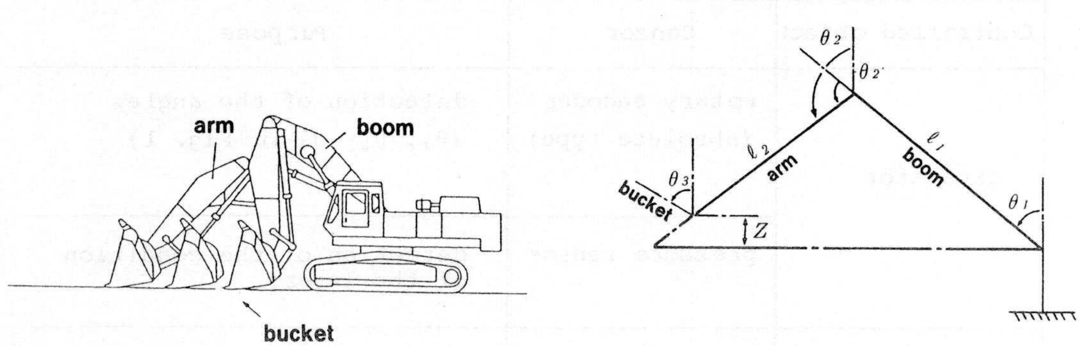

Fig.1 Level crowding of an excavator and its frame model

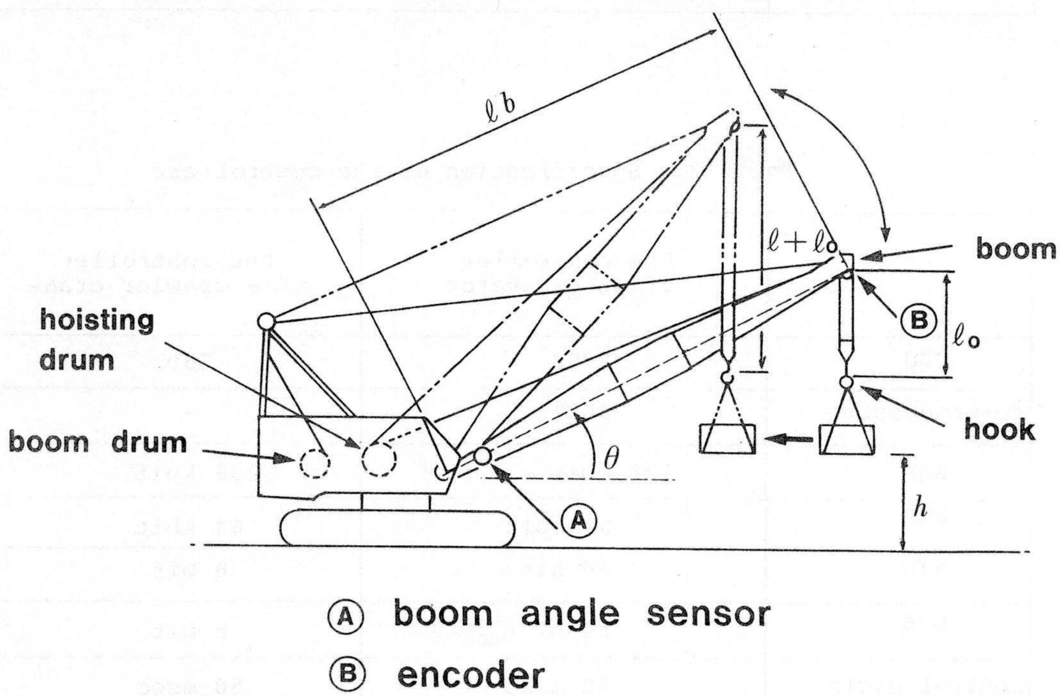

Fig.2 Level luffing of a crawler crane

Table 1. Sensors and their purpose

Controlled object	Sensor	Purpose
excavator	rotary encoder (absolute type)	detection of the angles (θ_1, θ'_2 θ'_3 in Fig. 1)
	pressure sensor	detection of the condition of the levers
crawler crane	angle sensor (inclinometer)	detection of the boom angle to the ground
	rotary encoder (incremental type)	detection of the rope travel
	pressure sensor	detection of the condition of the levers
	tachometer	detection of the engine speed

Table 2. Specification of the controllers

	the controller of an excavator	the controller of a crawler crane
CPU	8088	Z80
co-processor	8087	-
ROM	128 kbit x 3	256 kbit
RAM	64 kbit	64 kbit
A/D	10 bit	8 bit
D/A	10 bit	8 bit
control cycle	50 msec	50 msec

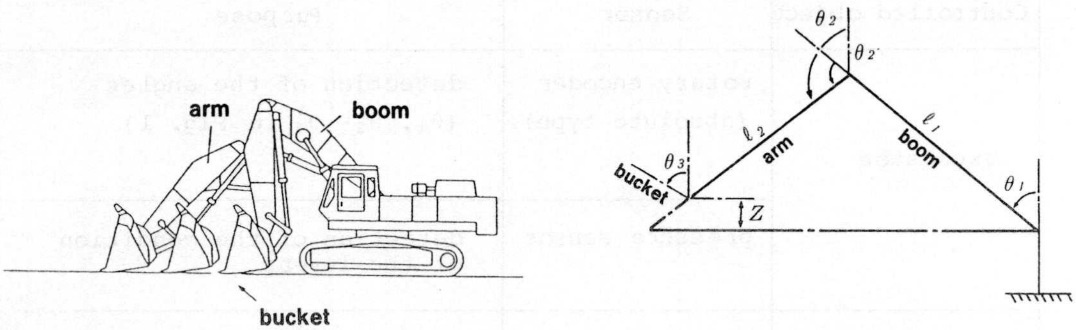

Fig.1 Level crowding of an excavator and its frame model

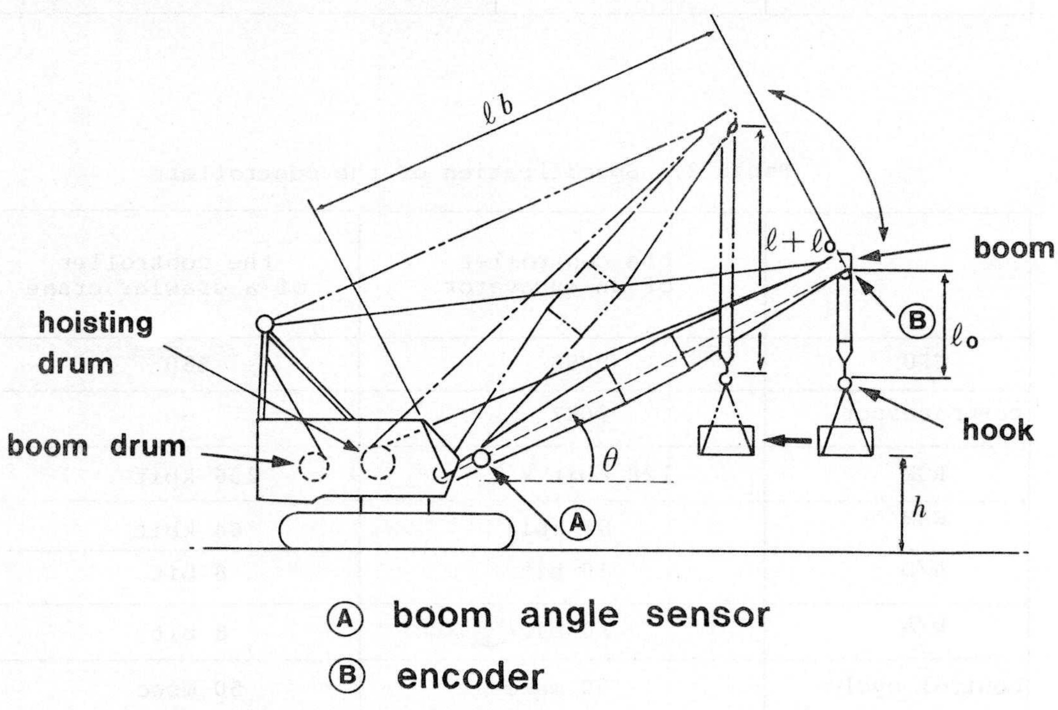

Fig.2 Level luffing of a crawler crane

(2) The control error at the beginning of the level crowding can be reduced when the lever condition is used, because the time delay of the boom actuator and that of the arm actuator are nearly equal

In articulated machines such as hydraulic excavators, dynamic characteristics are greatly susceptible to the attitude. Therefore, it is difficult to control the machine stable at all attitudes with constant gain. To solve this problem, the adaptive gain is characterized as a function of two variables, $\theta 2'$ and Z.

The block diagram of the control system is shown in Fig.4.

3.3 Level luffing control of a crawler crane

In Fig. 2, the desired value of rope travel l' is given as follows:

$$l' = lb. (\sin \theta - \sin\theta o) \qquad (3)$$

where lb : boom length
θ : boom angle
θo: initial boom angle

The control error of the height of a load is obtained as follows:

$$\Delta h = l'-l \qquad (4)$$

here Δh : control error of the height of the load
l : real rope travel

The feedback control value Ub is calculated by Δh as follows:

$$Ub = (Kp + Ki/s)\cdot \Delta h \qquad (5)$$

where Kp : proportional gain
Ki : integral feedback gain

Differentiating both sides of Eq.(3) with respect to time, Eq.(6) is obtained :

$$dl'/dt = lb\cdot\cos\theta\cdot d\theta/dt \qquad (6)$$

The feedforward control value is obtained by Eq.(6), because the speed of the rope travel is controlled by the output to the hoisting drum. The manual operating lever position is used also in this control system instead of the angular velocity.

The crane presented in this paper has the hoisting drum driven by two hydraulic pumps. Fig.5 shows the relation between spool displacement and the open area of the control valve. There is saturation of speed (the maximum speed of the first speed) related to the capacity of the first hydraulic pump (Dl in Fig.5). A dead band appears until flow from the second pump (the second speed) is added. The width of the dead band varies according to the engine speed. A dead band exists also in the vicinity of the zero point (DO in Fig.5).

The widths of the two dead bands are so great that they have a significant effect on the control performance. Therefore this non-linearity must be compensated using the information on the engine speed.

In order to reduce both the swing of a load and the control error at the beginning of the level luffing control, acceleration of the boom is regulated for a fixed period after the start of the level luffing. The controller generates the start pattern for the period. The electromagnetic proportional reducing valve of the boom is driven by the start pattern and the acceleration of the boom is regulated. After the period is ended, the electromagnetic proportional valve of the boom is fully open and the boom is operated manually. The boom pilot line of the hydraulic system is available for this method. The feedforward control value is increased in accordance with the start pattern.

The following control parameters are modified according to the engine speed:
(1) feedback gain - In order to prevent an oscillatory response, the faster the engine speed becomes, the smaller the Kp must be.
(2) start pattern - The faster the engine speed becomes, the lower the increasing rate of the start pattern must be, in order to prevent the abrupt movement of a load.
(3) feedforward gain - This modification compensates for the slight imbalance between the boom and the hoisting speed.
(4) non-linear compensation - This corresponds to the change of width of the dead band according to the engine speed.

The block diagram of the control system is shown in Fig. 6.

4. Results of Field Tests

4.1 Level crowding control of an excavator

4.1.1 Effects of feedforward control

In the case of position feedback only, increasing gain Kp to decrease error Δz causes oscillation due to the time delay in the system, as shown by "OFF" in Fig. 7. That is, Kp cannot be increased. Application of the feedforward of the arm lever value described in section 3.1 can decrease error without increasing Kp, as shown by "ON"in the figure.

4.1.2 Effects of gain modification with attitude

Level crowding is apt to become oscillatory at the raised position or when crowding is almost completed. This oscillation can be prevented by changing gain Kp according to the attitude, as has been discussed in section 3.2. The effect is shown in Fig. 8. This shows the result when level crowding was done at about 2 meters above ground. Compared to the case without gain modification, denoted by OFF in the figure, the ON case with compensation provides a stable response.

4.2 Level luffing control of a crawler crane

Fig. 9 shows the successful results of the control application tests using a crane with a boom length of 27.4m.

Fig. 10 shows the result of control performance tests using a tower crane with a tower boom length of 53.6m and a jib length of 45.7m. In order to keep the control system stable, the feedback gain must be low, because the rigidity of the tower crane structure is lower than that of the crane mentioned before.

CONCLUSION

Control systems for construction machinery have been developed and their control performance has been verified. The results can be summerized as follows :

(1) The stable and accurate control performance has been achieved by the application of both the feedforward control and the feedback control.

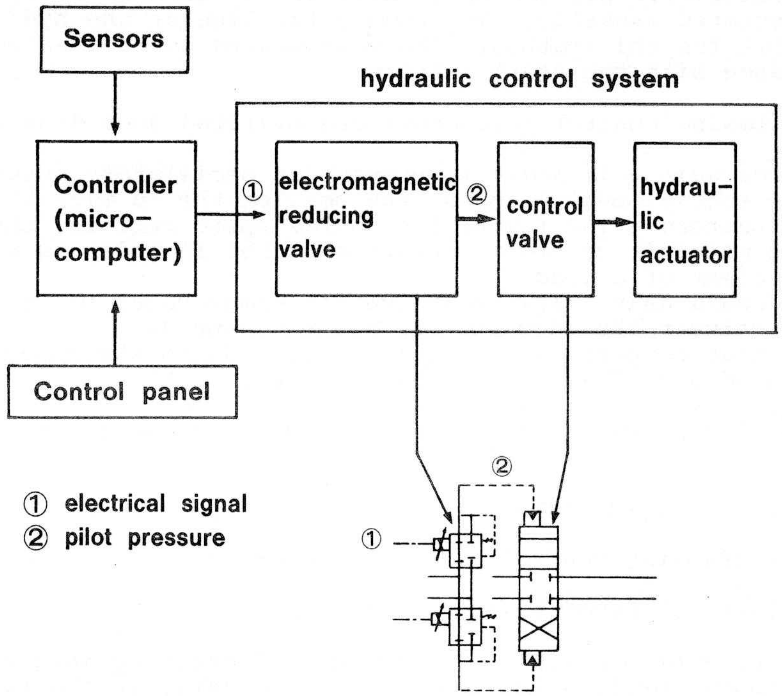

Fig.3 System components

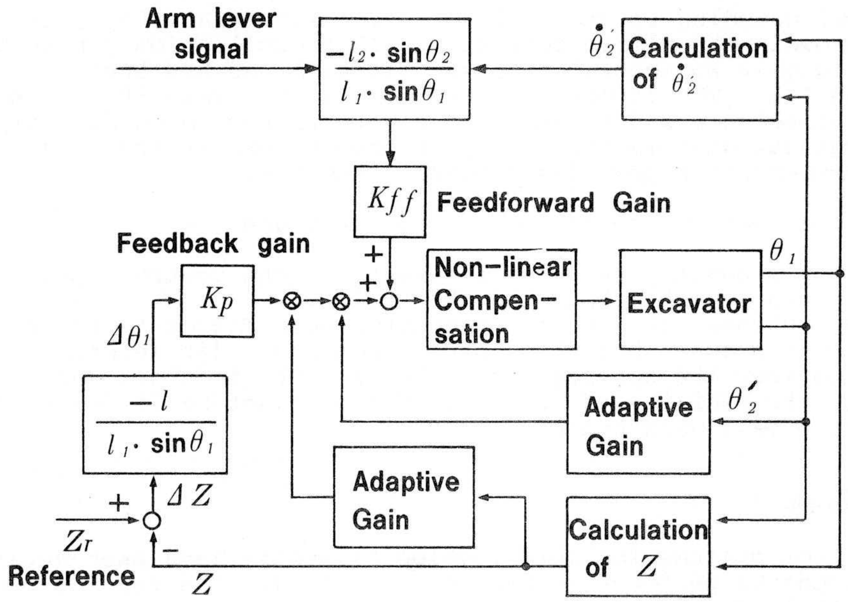

Fig.4 Block diagram of level crowding control system

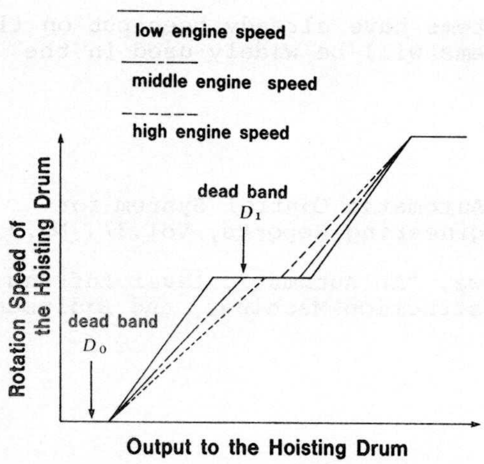

Fig.5 Rotation speed of hoisting drum

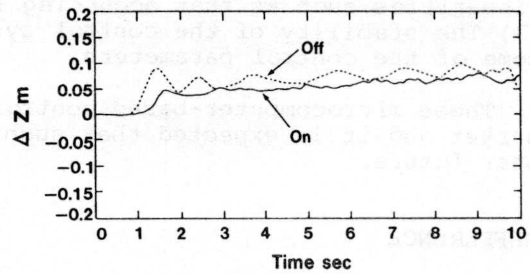

Fig.7 Effect of feedforward control on control error of Z

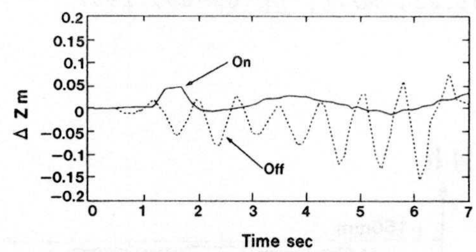

Fig.8 Effect of adaptive gain control on control error of Z

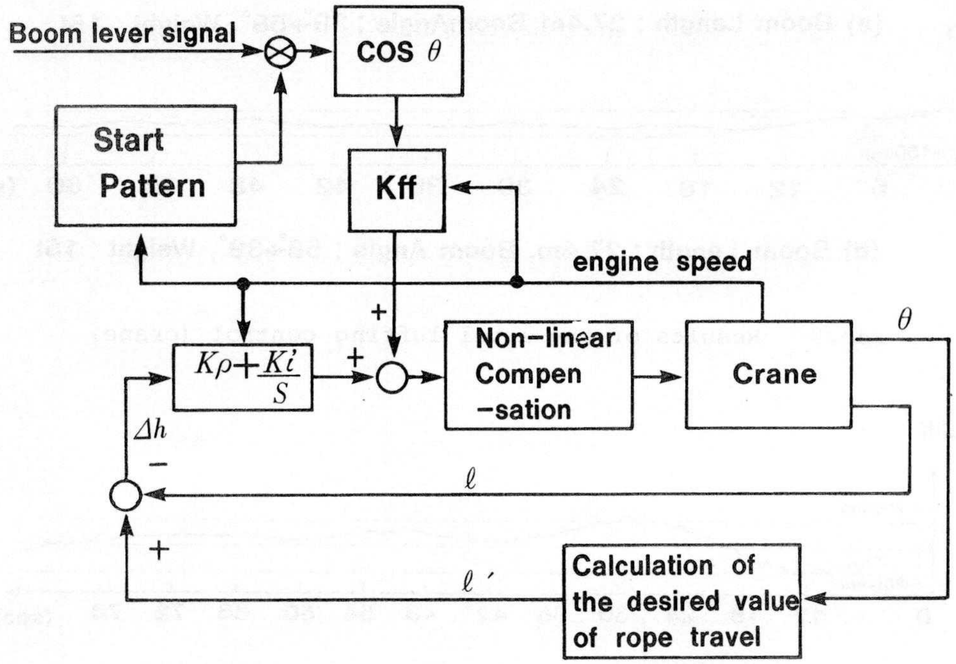

Fig.6 Block diagram of level luffing control system

(2) The control error has been reduced by compensating the strong non-linearities such as that occurring in the dead bands.
(3) The stability of the control system has been improved by modifying some of the control parameters.

These microcomputer-based control systems have already been put on the market and it is expected that such systems will be widely used in the near future.

REFFERENCE

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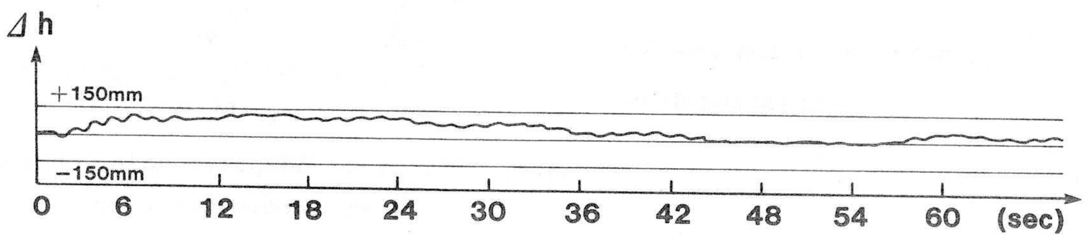
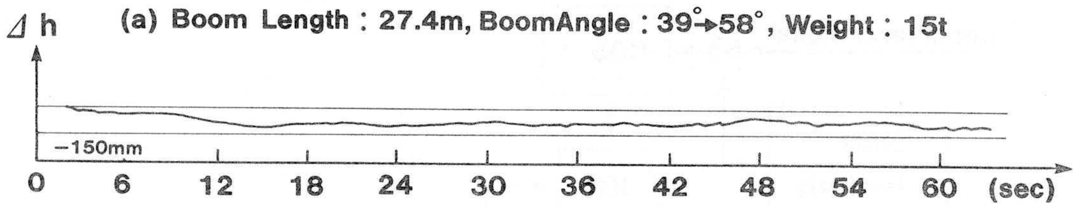
2) N. Sugimoto, M. Kakuzen and H. Kinugawa, "An Automatic Level Luffing Control System for Crawler Cranes." Construction Machinery and Equipment, Vol.23, No.7, pp 65-69, 1987



(a) Boom Length : 27.4m, BoomAngle : 39°→58°, Weight : 15t



(b) Boom Length : 27.4m, Boom Angle : 58°→39°, Weight : 15t

Fig.9 Results of the level luffing control (crane)

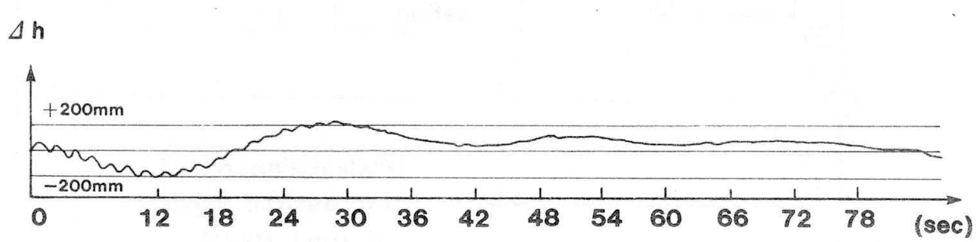


Fig.10 Result of the level luffing control (tower)