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OPERATION SYSTEM FOR HYDRAULIC EXCAVATOR FOR DEEP TRENCH WORKS

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ABSTRACT

Results of the experimental analysis of the operation system of a hydraulic excavator for deep trench works are described in this paper. The system of the operation of a hydraulic excavator has a hierarchical structure. The system is a sequentially controlled system which is consist of several partial systems in rough figures. And also there are various job items in each separated state of operations. Since these operations are organized in a network system as the event driven system, the analysis of the oparation system is came to describe the conditions which drive the system by using measured values of the system condition. As such physical values, displacement and velocity of hydraulic cylinders and hydraulic pressure values of the cylinders are used.

As the results of analysis, methods of determining the time at a bucket is in contact with the ground, over loading and the end of the excavation are presented in this paper.

1. INTRODUCTION

Hydraulic excavators are excavation and loading machines having the construction shown in Fig. 1. Work by the excavator is performed by contraling the hydraulic power of the swivel motor and the hydraulic cylinders for the boom, arm and bucket. This control is performed by the operator who adjusts the opening of the hydraulic switching valves.

If the work of the hydraulic excavator is seen as a control system, then the operator is equivalent to the controller, and the control system has the opening of the hydraulic valves as its immediate objective and the position and angle of bucket as the ultimate objective. The work of hydraulic excavators is relatively sequential but in the strict sense, the same motion is hardly ever repeated. This occurs because the sediment that forms object of the work is removed by excavation, and because the excavating position and the conditions of the substance to be excavated will vary in an uncertain manner. The operator responds to these conditions, determines the next operation to be performed in sequence and skillfully advances the work. The operator can be thought of as an extremely excellent controller.

For automating the work of hydraulic excavators, a control system for determining the contents of operation in response to the situation of the work is required in addition to the conventional feedback control technique for controlling the amount of extension of the individual hydraulic cylinders. The control system of the former is a system that simulates the information detection and judgment processes of the operator. In this case, the contents of the work change in response to the situation and because the situation varies in accordance with the work, this system is therefore equivalent to an "event-driven system".

This control system determines the position of the hydraulic excavator and the situation for the object of work from input information and then determines the next operation. In addition, this kind of control system requires a considerable amount of time to analyze and process the input data and this cannot be neglected. Therefore, it requires a predictive control which can predict the situation when the control signals are output, and perform control in accordance with these predictions.

2. Hydraulic Excavator Operating State and Control System

2. 1 Model of Control System

The operation of hydraulic excavators are relatively sequential, and most of the ordinary work consists of the repetition of (1) moving the bucket to the excavating position, (2) excavation, (3) moving the bucket to unloading position and (4) unloading. Fig. 2 shows a network model of hydraulic excavator for deep trench work, and shows that the operation forms a sequential chain system.

Table 1 Driving conditions of the network model

Item	Meaning	Symbol	Purpose of operation	Driving condition
A	Moving to un-loading posi-tion.	Aa	Moving up to ground level (G. L.)	Excavation point is lower than G. L.
		Ab	Moving to unloading position (no turning)	Present position is not the unloading position.
		Ac	↑ (with turning)	↑
		Ad	↑ (not spilling mud with no turning	Bucket is too tilt to move.
		Ae	↑with turning	↑
B	Un-loading	Ba	Unloading	Position and status is good.
		Bb, Bc	Unloading with moving	↑ leveling work
C	Moving to excava-tion posi-tion	Ca	Moving down to G. L.	Excavation point is lower than G. L.
		Cb	Moving to excavation position (no turning)	Present position is not the excavation position.
		Cc	↑ (with turning)	↑
		Cd	↑ bucket status is for excavating (no turning)	Bucket status is not for excavating.
		Ce	↑ (with turning)	↑
D	Excava-tion	Da	Excavating	Position and status is good
		Db	↑ and loading	Not fill up
		Dc	Loading	Complete excavation
		Dd	Excavation for leveling	↑ leveling work

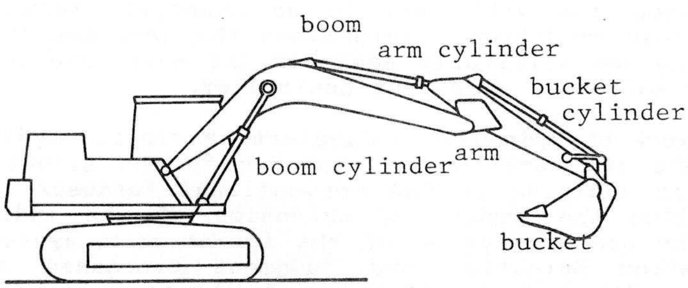

Fig.1 Hydraulic power shovel.

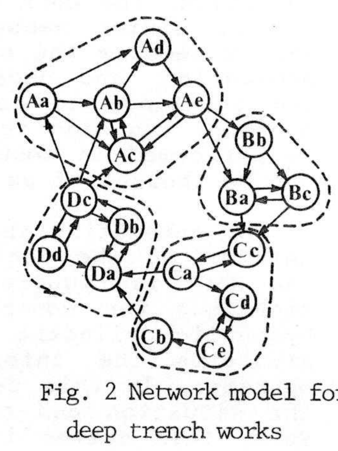

Fig. 2 Network model for deep trench works

However, even though the purpose of operation is the same, the actual operation by the operator varies with the conditions of hydraulic excavator, and the nodes between operations do not have inevitable times. The "operations" stated here were identified as operation patterns according to the control levers used, and correspond to the purpose(intention of the operator) shown in Table 1. When an operator selects a particular operation, there is some reason that makes the selection inevitable, and this reason becomes a driving factor in the hydraulic excavator system. This is the meaning of the driving conditions shown in Table 1. In such an event-driven system[1], a particular operation pattern is inevitably selected when the purpose of operation and the driving conditions are given.

However, the driving conditions shown in Table 1 give "meanings" to the conditions of hydraulic excavator, and these meanings must be determined from measured values. In order to quantify the control model, it is necessary to determine a method of discriminating the meanings and corresponding to all the driving conditions shown in Table 1. Of these conditions, the results of analysis will be presented here only for (1) the bucket teeth ground contact position, (2) overload during excavation, and (3) the completion of digging.

2.2 Method of Determining Teeth Contact

For shifting the bucket from moving to excavating motion, it is necessary to determine whether the bucket teeth are in contact with the ground to be excavated. Fig.3 shows an example of the measurement of the hydraulic signals at the bottom of boom cylinder through the filter of Eq.1.

$$\tilde{X}_k = 0.675X_k + 0.25X_{k-1} + 0.125X_{k-2} \tag{1}$$

From this figure, it will be known that, when the bucket is in contact with the ground, the hydraulic pressure decreases and the rate of change per unit time becomes larger. This means that the grounding can be determined from the hydraulic signals from the cylinder. In this

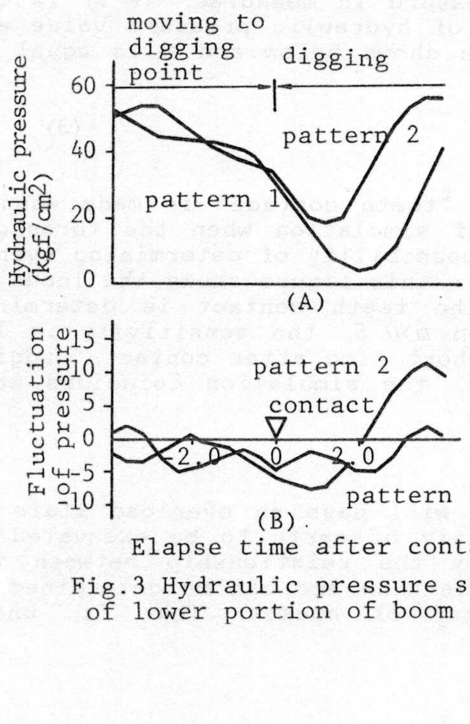

Fig.3 Hydraulic pressure signal of lower portion of boom cylinder

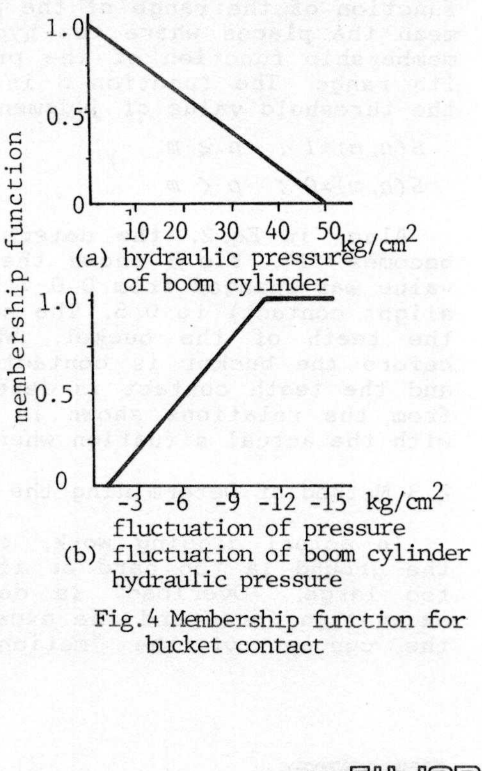

Fig.4 Membership function for bucket contact

analysis, the method of judging the grounding was reviewed on the basis of the hydraulic pressure values for the hydraulic signals at the top and bottom portions of the boom cylinder, the bottom portion of arm cylinder and the bottom portion of the bucket cylinder.

The hydraulic values and their fluctuations vary with the angle of bucket in the process of moving to the ground and the hardness of ground to be excavated, and it is normally difficult to form an apriori determining them on the cases of measured values. Because of this, the model to be used for this purpose must be one which incorporates the uncertainty of data as a premise. A "fuzzy set model" is one such kind of model. Fig. 4 shows the membership function, which was given beforehand for the "grounding judgment" of hydraulic value and the fluctuation value. As this function approaches "1", there is greater surety of determination as the grounding becomes greater. This means that the membership function for the "determined as grounding" set is higher. In the case of hydraulic pressure at the lower end of the boom cylinder, the hydraulic pressure value is close to zero, and the probability of occurrence of "determined as grounding" becomes higher as the fluctuation value increases, i. e. the hydraulic pressure decreases suddenly.

In the teeth contact, the hydraulic pressure must be low and the pressure range must be large as shown in Fig. 4, so that both have a relationship of a product set (in fuzzy sets, an expression is made by using a function which has the smallest membership function) with respect to "determination as teeth contact". However, if signals are obtained from different measuring places as in the case of the hydraulic pressure values for the boom cylinder and the arm cylinder, there are no significant correlations in the data showing the teeth contact of the bucket. Because of this, the teeth contact is determined here by using Eq. 2

$$A = S\{S(P_1 \cdot V_1, m)+S(P_2 \cdot V_2, m)+S(P_3 \cdot V_3, m)+S(P_4 \cdot V_4, m)\} \qquad (2)$$

where, P is the hydraulic pressure value; and V is the membership function of the range of the pressure value, while the subscripts 1 to 4 mean the places where the hydraulic pressure is measured. $(P \cdot V)$ is the membership function of the product set of hydraulic pressure value and its range. The function S is defined as shown below and m is equal to the threshold value of judgment.

$$\left.\begin{array}{ll} S(n,m)=1\ ; & n \geqq m \\ S(n,m)=0\ ; & n < m \end{array}\right\} \qquad (3)$$

Also, in Eq. 2, the determination of "teeth contact" is made when A becomes "1". Fig. 5 shows the results of simulation when the threshold value was changed from 0. 0 (there is a possibility of determining even a slight contact) to 0. 5. The solid line in this figure shows the locus of the teeth of the bucket. When $m>0$, the teeth contact is determined before the bucket is contacted and when $m>0.5$, the sensitivity is low and the teeth contact is determined a short time after contact. Judging from the relations shown in the figure, the simulation coincides well with the actual situation when m is 0. 15.

2. 3 Method of Determining the Overload

In actual digging work, the machine will have an overload state if the ground is too hard or if the quantity of earth to be excavated is too large. "Overload" is determined by the relationship between the excavation force and the excavation resistance and can be determined by the concept of the "motion smoothness" of bucket. That is, under overload conditions, the hydraulic cylinder may stop or perform an avoidance operation, by which the extension speed of the cylinder may suddenly rise so that its motion is no longer smooth. When the motion is smooth, the extension speed of the hydraulic cylinder becomes a constant value (V_u) as long as the hydraulic valve is fully open, making it possible to determine the overload by using the speed (V_M) of hydraulic cylinder. Also under the overload conditions, the duration must be carefully examined. Even if the excavation resistance exceeds the excavation force for a certain period of time, the overload situation disappears when the extension speed of hydraulic cylinder returns to predetermined value. From the above, the following model was therefore adopted by using U as the value for determining the overload.

$$F(t) = a \cdot V_u - V \cdot M(t)$$

$$\begin{aligned} &\text{a)}\ A(t) = 0 &&;\ F(t) \leqq 0 \\ &\text{b)}\ A(t) = A(t-1) + F(t) &&;\ F(t) \geqq F(t-1) \qquad (4) \\ &\text{c)}\ A(t) = A(t-1) + \{1 - V \cdot M(t)/a \cdot Vu\} &&;\ F(t) < F(t-1) \end{aligned}$$

$$U = S[\max\{A_1(t), A_2(t), A_3(t)\}, m] \qquad (5)$$

Where, A is a variable for the shortage (stress) of extension speed of the cylinder under the overload state, and subscripts 1 to 3 respectively show the cylinders for the boom, arm and bucket. Here "a"

Table 2 Category Score

Item	category	score
length of excavation	> 30cm	-9.8
	30 ~ 50cm	-17.9
	50 ~ 70	-17.0
	70 ~ 90	3.7
	90 ~100	14.6
	100 ~120	43.6
	120 over	53.1
decrease in pressure of boom top	> 20kg/cm²	-1.1
	20 ~ 30kg/cm²	10.5
	30 ~ 40	-4.4
	40 ~ 50	-12.0
	50 ~ 60	21.5
	60 ~ 70	43.5
	70 ~ 80	-30.5
increase in pressure of boom bottom	> 20kg/cm²	4.7
	20 ~ 30kg/cm²	2.3
	30 ~ 40	-16.5
	40 ~ 50	13.6
	50 ~ 60	8.1
	60 ~ 70	40.3
increase in bucket top pressure	> 20kg/cm²	-10.6
	20 ~ 30kg/cm²	-19.4
	30 ~ 40	31.1
	40 ~ 50	82.8
	50 ~ 60	96.7
	60 ~ 70	91.9
boom bottom pressure	> 30kg/cm²	-22.5
	30 ~ 50kg/cm²	-2.4
	50 ~ 70	9.0
	70 ~ 90	-6.8
mean value	42.5	

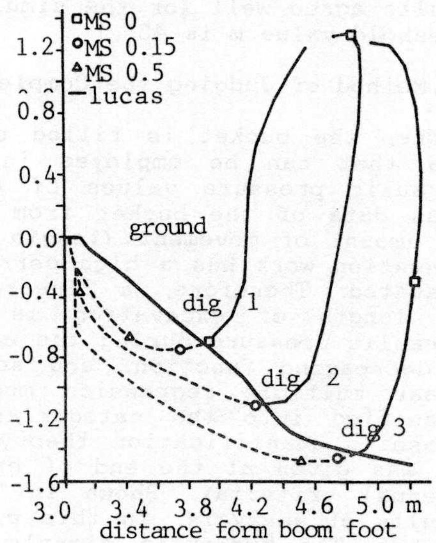

Fig.5 Simulation of bucket contact

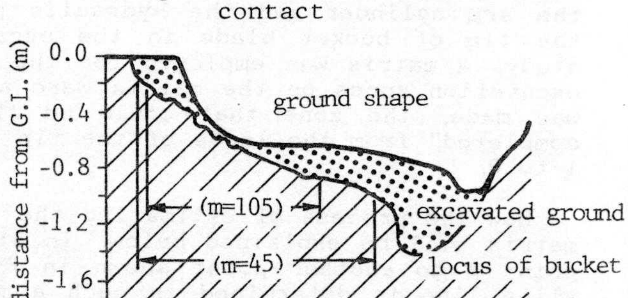

Fig.6 Simulation of overload

is a coefficient considering the efficiency of the hydraulic cylinder in operation, and 0.9 was used for "a" in the process of calculations. Also, the function "max" is the function which takes the maximum value out of the arguments, while S is the function defined by Eq. 3. In this model, the shortage of speed of every hydraulic cylinder is accumulated, and an overload is recognized when the maximum value of shortage for every cylinder exceeds "m". However, the model is set in such a manner that the speed of recovery will increase when signs of recovery from the overload state are recognized. For example, if the extension speed of a cylinder exceeds 90% of the predetermined speed, then the condition a) is immediately applicable and A becomes zero. In this model, A will accumulate the stress in the stage where the speed of cylinder gradually decreases and "overload" state is progressing but, if the speed of the cylinder rises, the stress decreases in response to the rate of the rise in speed of the cylinder.

Fig. 6 shows the results of simulation on the basis of the data obtained when the trench work is being carried out with a slight overload. This is the example when the operator judged an overload immediately after the start of excavation and carried out the work while performing avoidance operation. It can be therefore seen that the results agree well for the simulated state and the actual state when the threshold value m is 45.

2.4 Method of Judging the Completion of Excavation

When the bucket is filled up, the digging action has to be ended. Data that can be employed in this model for determination are the hydraulic pressure values of each hydraulic cylinder as well as the locus data of the bucket from the start of excavation. In particular, the amount of movement (length of excavation) of the bucket during the excavation work has a high correlation with the quantity of earth to be excavated. Therefore, a linear multiple regression model mainly using the length of excavation is adopted as this model. However, the hydraulic pressure during the excavation work shows no simple increasing or decreasing function, and so it is not possible to merely apply a linear multiple regression model. Because of this, each factor was classified into the categories shown in Table 2, and the model of Hayashi's quantification theory type 1 was used (the dummy variable of 100 was given at the end of excavation and of 0 during its process as external criteria). Shown in Table 2 are the category scores in the results of analysis. In this case, the multiple correlation coefficient is 0.9. The hydraulic signals of the arm cylinder are not used here because there is a high correlation between the hydraulic pressure of the arm cylinder and the hydraulic pressure of bucket cylinder during the tip of bucket blade in the excavation made in the past. In this study, a matrix was employed for the coordinates of the ground, and the excavation zones on the matrix were all set to "1". When the excavation was made, the zone that could be theoretically judged as "excavation completed" from the locus of the tip of bucket blade, was converted from 1 to 0.

Now the process of estimating the excavation start position from this matrix will be explained below. In step 1, the slice line is moved from point A to another point shown in Fig. 8, and then the equation of the slice line is determined in such a manner that earth volume within the quadrangle ABS_1S_2 becomes equal to the predetermined volume. In step 2, the "presence or absence of earth" from S_1 to S_2 on the slice line is determined, and the coordinates (P_2), at which the presence of earth is first recognized, is then determined. This is shown by S_2 in Fig. 8. In step 3, "the presence of earth" is determined in the positive direction on the horizontal line of P_1, and the coordinates (P_2), at which the presence of earth is recognized last, is established. This is shown by B in the Fig. 8. In step 4, "the presence of earth" is determined in the same manner in the positive direction on the vertical line of P_2, and the coordinates (P_3), at which the presence of earth is recognized last, are established. This P_3 is the required coordinates of the start point of excavation.

The following will explain the method of determining the excavation patterns. This actually means how to extend the boom and arm. The optimum excavation pattern can be obtained by drawing a locus which can provide the tip of bucket blade in the excavation made in the past. In this study, a matrix was employed for the coordinates of the ground, and the excavation zones on the matrix were all set to "1". When the excavation was made, the zone that could be theoretically judged as "excavation completed" from the locus of the tip of bucket blade, was converted from 1 to 0.

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The following will explain the method of determining the excavation patterns. This actually means how to extend the boom and arm. The optimum excavation pattern can be obtained by drawing a locus which can provide a proper earth volume inside the bucket. However if the excavation is too deep, the probability of the occurrence of overload becomes higher and smooth operation cannot be performed. Therefore, in this study, it was decided to estimate the virtual excavated earth volume by providing the excavation patterns stated below.

(1) Only the arm cylinder is extended.
(2) The boom cylinder is shortened by 20% of the arm extension.
(3) Only the arm cylinder is stretched after vertically excavating the predetermined amount.
(4) The boom cylinder is extended by 20% of the extension of the arm after horizontally excavating the predetermined amount.

Now, the process of determining the excavation patterns to be adopted will be explained below by comparing the optimum earth volume [VT] and the virtual excavated earth volume [V] of the excavation patterns. In step 1, the following items are determined from V value obtained by (1):
During [$V \geqq 1.5VT$]: The excavation pattern with the boom cylinder extended by 10% of the extension of arm.
During [$0.5VT \leqq V \leqq 1.5VT$]: Excavation pattern with only the arm cylinder extended. During [$V < 0.5VT$]: Advancing to the next step. In step 2, the following items are determined from V value obtained by (2): During [$V \geqq 1.3VT$]: Excavation pattern with the boom cylinder shortened by 10% of

the extension of arm. During [0.7VT ≦V<1.3VT]: Excavation pattern with the boom cylinder shortened by 20% of the extension of arm. During [0.5VT≦V<0.7VT]: Excavation pattern with the boom cylinder shortened by 30% of the extension of arm. During [V<0.5VT]: Advancing to the next step. In step 3, the excavation pattern with only the arm cylinder extended after vertically excavating the predetermined amount if the coordinates of excavation start are on the line AB. In other cases, the excavation pattern with the boom cylinder extended by 20% of the extension of arm after horizontally excavating the predetermined amount. Fig.9 shows the results of simulation using this model for the excavation command within the zone of the quardrangle. These results are very good.

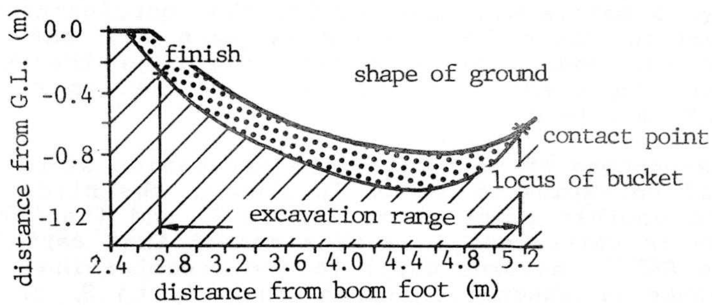

Fig.7 Simulation of completion of excavation

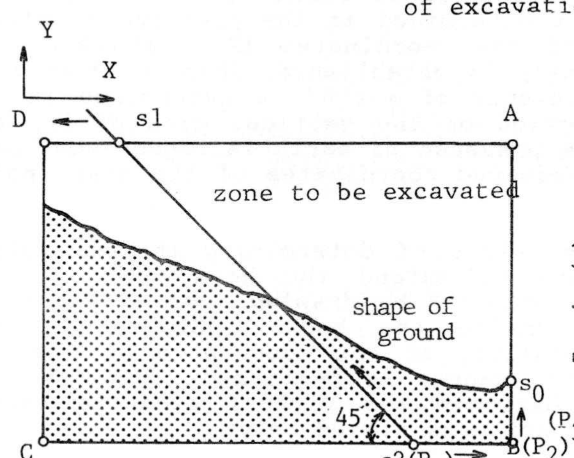

Fig. 8 Method of estimatingexcavation start position

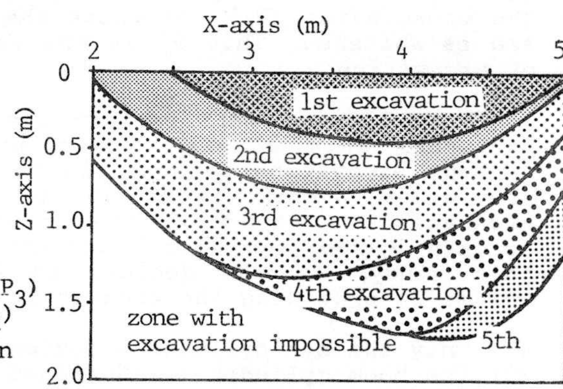

Fig. 9 Simulation of model

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