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SIMULATION AND CONTROL OF ROTARY SNOW PLOW

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Abstract: The operational control of the rotary snowplow is considered to improve its working efficiency. The speed of the rotary snowplow is controlled, so that the load to the rotary snowplow is kept constant. As the load can not directly be detected, some items considered for the controlled variable are, for example, the engine revolution, the load pressure and etc. In order to examine these, the working simulation of the rotary snowplow was considered by introducing the experimental equation of the load. The control methods were examined by means of the simple digital control using the personal computer. These control methods were compared with simulations and experiments.

Consequently, the working efficiency is improved about 20 % than the manual operation.

1. Introduction

A problem of clearing snow is important in a snow country, so that the automobiles increase all around. Clearing snow by machine can be classified into two groups. The one scratches and thrusts snow (a plow type), the other scratches and flies snow (a rotary type). In this paper, the authors described the car speed control of the rotary snowplow in the latter type. This was considered from both sides of the working simulation and the experiment to improve the working efficiency of the rotary snowplow.

2. Outline of Rotary Snowplow

The snow clearing method of the rotary snowplow is simple, as shown in Fig.1, snow is crushed and collected by the turning effort of an auger with a spiral nail, driven into a blower and cast out in an arbitrary direction by the centrifugal force of the blower and a chute.

These shapes differ a little by the maker, but the snow clearing method is same. Compared with the plow type, this method is absolutely necessary to clear deep snow and snow walls built by the snow clearing.

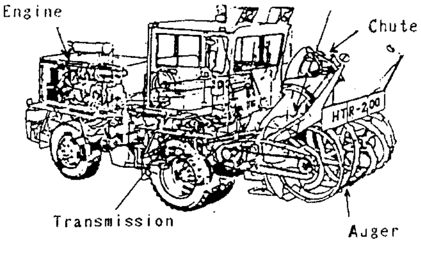

Fig. 1 Rotary snow plow.

Also, the rotary snowplow is conveniently used to load a truck with snow in the street and is very good on the wide road in pavements, freeways etc. Until now, the rotary snowplow was mainly large power, recently it has power as low as 8 Kw to clear snow from a private road of the home. The snow clearing work of the rotary snowplow must be operated by balancing the driving power of snow clearing equipments (auger and blower) against running equipments (running wheel) for the load changing. The power source used is a Diesel engine. Fig.2 shows the power transmission system flowchart of the rotary snowplow (model HTR-200, Nippon Jyosetsuki Seisakusyo Co.) which appears on the market.

The engine power drives snow clearing equipments and running equipments through the gear transmission. The former has two stages for the change gear, the speed ratio between the blower and the auger is constant. For the rated rotational frequency of the engine (2000 r.p.m), the rotational frequency of the blower is 281 r.p.m with the low speed and 351 r.p.m with the high speed. The casting distance is about 15 meters and 25 meters respectively.

The latter is driven by the transmission through the hydraulic pump and motor in order to change the non-stage speed. In this case, the clearing maximum speed is about 7 km/h.

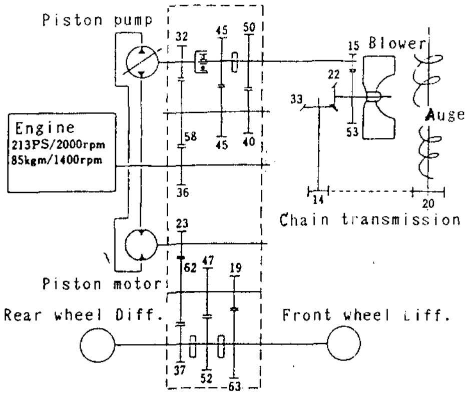

Fig. 2 Transmission system flowchart of the rotary snowplow.

3. Non-Stage Change Speed of Blower

The rotary snowplow uses the rated power of the engine against the snow clearing and the running equipments, but the driving power of the blower in the snow clearing equipment is about 70 % of the total power from the experimental examination [1]. Besides, as the casting power is consumed, the consumption power increases proportional to the square of the speed ratio for the rotational frequency of the blower.

Consequently, snow clearing capacity is 1300 ton/h in the low speed on the standard load, but it decreases to below 800 ton/h in the high speed. It is necessary for the efficient improvement of the rotary snowplow to make the casting distance more smaller. In this paper, authors designed the non-stage change speed equipment to set the necessary minimum casting distance in its place and it was equipped.

Fig.3 shows this power transmission flowchart. As the transmission efficiency had to be considered, the non-stage change speed equipment was designed as the hydro-mechanical type [2]. The transmission through the gear was until the minimum speed and from it to the maximum speed was added by the hydraulic pump and motor.

In order to add a mechanical input to a hydraulic input in the output, planet gears were used. It is necessary for the operator of this snowplow to adjust the running speed and to determine the running direction and to set the blower speed. As these operations become the very large load for the operator and the balance of the running speed to changing the clearing load is difficult, the drop of the efficiency can not be avoided. Then, in order to improve the efficiency and to decrease the load of the operator, the automatic operation was realized by using the micro-computer as a controller.

Consequently, the operator may do only the direction operation of the rotary snowplow. The setting and the actuating of the blower revolution speed were given by changing the flow of the hydraulic pump in the change speed equipment. As the pump used a swash plate type axial piston pump, the construction of the servomechanism systems was necessary to change the tilting angle of the swash plate. Also, the running speed was similarly controlled by changing the swash plate angle. Fig.4 shows the total construction of control and actuator equipment.

4. Working Simulation

In order to simulate the working state of the rotary snowplow, the transfer function for the each factor and the load disturbance for the snow clearing state (height, speed, density etc.) must be obtained. These are classified into engine systems, snow clearing systems, running systems and load disturbance systems. The results classified are described as follows.

4.1 Engine systems

The engine is Diesel engine (Nissan PD6T type, rated output: 156Kw/2000r.p.m, maximum torque: 833Nm/1400r.p.m). The transfer function the torque versus the revolution speed of the engine can be written as follows:

$$TE = \frac{Ke}{1+TeS}(TE - TLE) \qquad \cdots(1)$$

where NE: engine revolution speed,
TE: engine torque,
TLE: engine load torque.

The engine torque is determined by the fuel injection flow etc. Here, an approximate equation is introduced from the performance curve the torque versus the fuel flow in the linear region. Also, the fuel flow is controlled by the governor (Bosch RSV type, mechanical all speed governor).

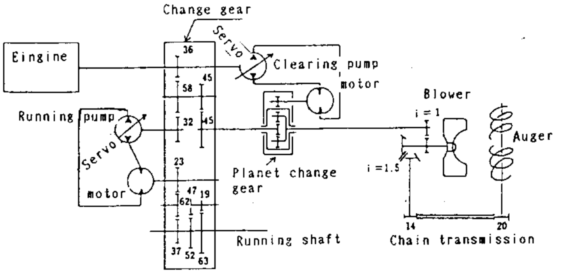

Fig. 3 Improved transmission flowchart.

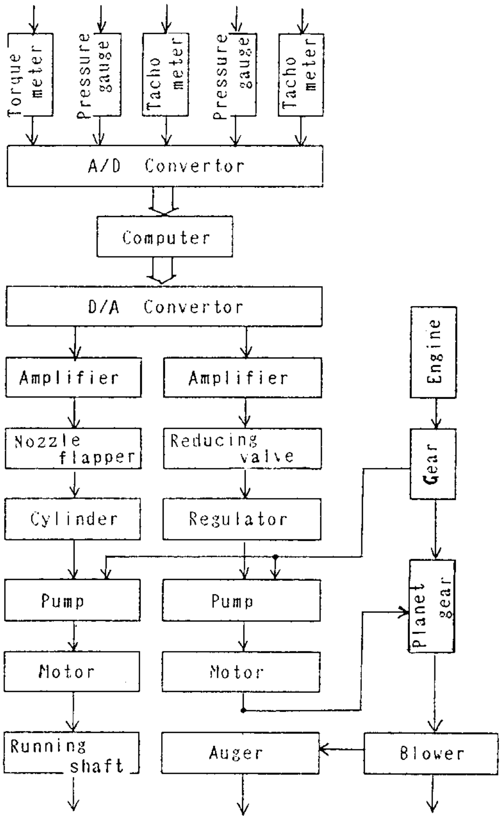

Fig. 4 Construction flowchart with regard to control and actuator equipments.

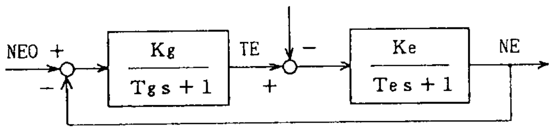

Fig. 5 Block diagram of engine systems.

The transfer function the engine torque (TE) versus set engine revolution speed (NEO) is approximated by the first order lag, because the speed of the overall response is slower, although the relation between the stroke of the governor and the engine revolution speed is the second order lag. Fig.5 shows the block diagram of the engine systems.

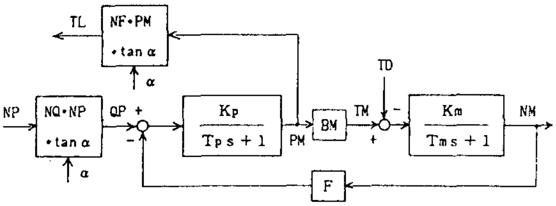

Fig. 6 Block diagram of pump and motor systems.

4.2 Snow clearing systems

Snow clearing systems are driven by the hydraulic pump and motor, by the gear. The revolution speed of the motor is changed by the swash plate angle of the pump. This tilting angle is controlled by the regulator and the electromagnetic proportional pilot valve with the current control. As the response regard to this servo-system which compares with the other motion systems is quick, the servo-system may be shown by the proportional factor. Fig.6 shows the block diagram of the pump revolution speed (NP) and the swash angle (α) versus the motor revolution speed (NM). The output equation of the revolution speed with regard to the non-stage change speed can be written as follows:

$$NB = \frac{\rho}{1+\rho} \cdot NS + \frac{1}{1+\rho} \cdot \frac{G_1}{G_2} \cdot NM \qquad \cdots(2)$$

where NB: output revolution speed (blower speed),
ρ: radius ratio of planet gear,
NS: input revolution speed of planet gear,
G_1,G_2: gear tooth number of motor shaft and ring.

4.3 Running systems

The running shaft is driven by the hydraulic pump and motor similar to the snow clearing systems. Consequently, its block diagram is same.

4.4 Load disturbances

In order to do the working simulation of the rotary snowplow, it is necessary to describe the load equation against the snow clearing equipment and the running equipment. The load against the snow clearing can be written as follows by the experimental equation with regard to the torque of the driving shaft of the blower.

$$T_w = 22.71 \cdot \sigma \cdot H \cdot V \cdot NB^{0.72} \qquad \cdots(3)$$

where T_w: load torque of blower driving shaft,
σ : snow density,
H: clearing height,
V: clearing speed.

Generally, the running resistance of a car consists of the rolling, the air, the accelerating and the grade resistances. The resistance of the laying snow is added in the case of the rotary snowplow. The load torque of the running shaft can be written as follows by considering a smooth road and a low clearing speed.

$$T_r = 0.29V + 9.55H + 3.17/\sigma - 2.19 \qquad \cdots(4)$$

4.5 Simulation and consideration

Fig.7 shows the overall block diagram discussed in Art. 4.1 4.4. In the simulation and the experiment, the control equation is given to control α_r (the tilting angle for the running speed change) and α_b (the tilting angle for the blower speed change). An example of the result is shown to compare the simulation with the experiment. The snow clearing conditions are shown in Table 1. The results simulated and experimented are shown in Fig.8 and 9.

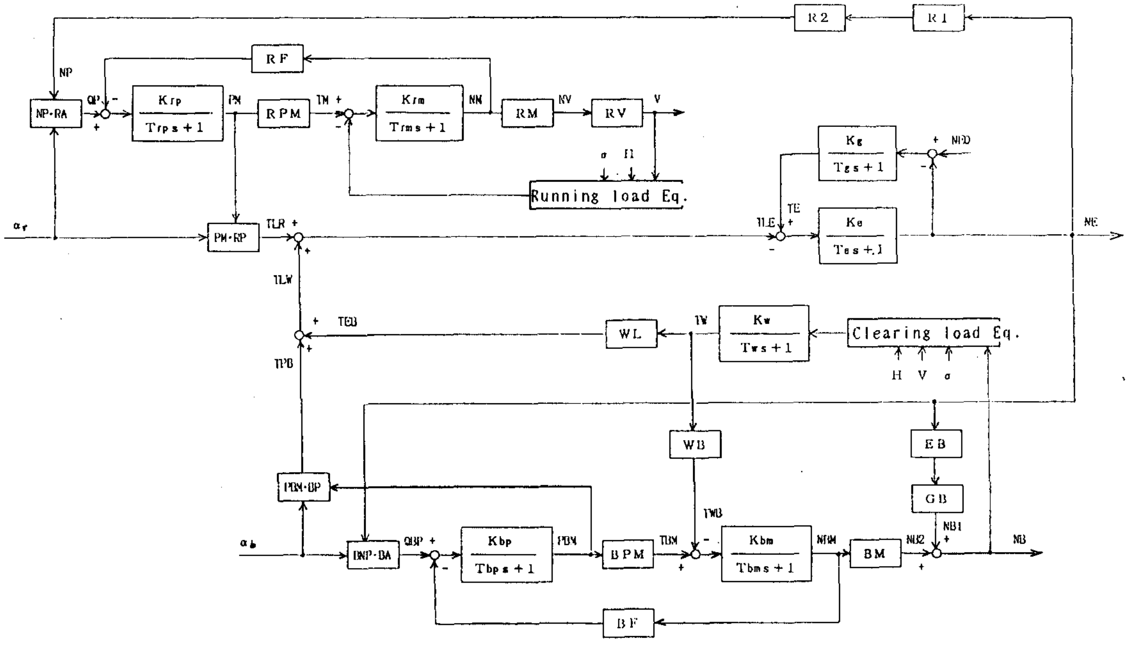

Fig. 7 Overall block diagram of the rotary snowplow.

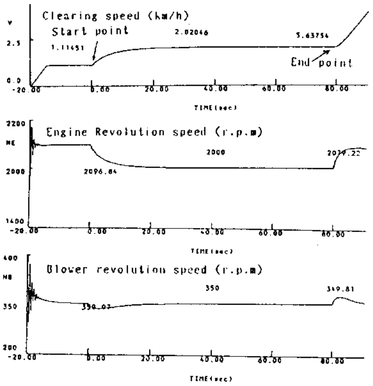

Fig. 8 Simulated result.

Table 1 Conditions of simulation and experiment.

Clearing conditions		Clearing height	0.38 m
		Snow density	0.30 g/cm
		Clearing width	2.60 m
Control conditions		Sampling time	0.05 sec
	Blower	Set blower speed	350 r.p.m
		Proportional gain	1
		Integral time	1 sec
	Clearing	Set engine speed	2000 r.p.m
		Proportional gain	0.02
		Derivative time	0.1 sec

In the simulation the load equation is important. It is difficult to describe decisively the load experimental equation, because the condition of the laying snow is complicated. Consequently, it seemed appropriate to consider the maximum-minimum band in the load experimental equation by using the many data and the data of a different year. But it differs little in our experiment. The simulation agrees well with the experimental results according to Fig.8 and 9. The simulation of the rotary snowplow is possible by means of a simple method. The results obtained by the simulation are summarized as follows.

(1) When the load response lag for the snow clearing equipments is large, it becomes a very unstable factor in the operation of the rotary snowplow.

(2) If there are oscillations of the clearing speed when the rotary snowplow rushes into the laying snow, it tends to occur a hunting run.

(3) In the operation of the rotary snowplow it may be well possible to control the clearing speed without controlling the blower revolution speed.

5. Load Control of Rotary Snowplow

In order to improve the working efficiency of the rotary snowplow, first is to efficiently apply the engine power into the snow clearing and the plow running equipments. It is necessary to eliminate a wasteful consumption of the power. As this was described in section 3, the rotary snowplow was improved by changing the two-stage of the blower speed into the non-stage. Consequently, the power of the snow casting becomes the minimum in the place of the snow clearing. But it is necessary to keep the blower speed constant.

Secondly, it is important to keep the load against the engine constant.

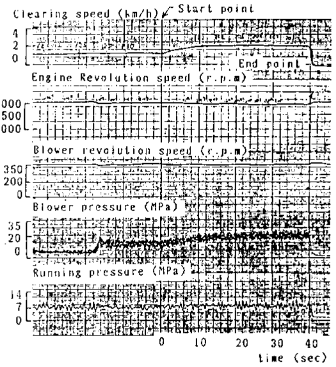

Fig. 9 Experimental result.

This is difficult for the operator, because he must control the snow clearing speed to keep the load constant. The working efficiency of the rotary snowplow is strongly influenced by the operator. Accordingly, we considered and realized the control of the snow clearing speed to keep the load constant, namely, the automatic operation.

5-1 Set and control of blower speed

As shown in Fig.7, the set and the control of the blower speed are manipulated by the tilting angle (α_b) of the pump swash plate. In this case, as a controlled variable (NB) can be directly controlled, the simple control equation is used as follows:

$$\begin{aligned}\theta_b(n) = {} & K_{bp}\left[e_b(n) + \frac{1}{T_{bI}}\left\{\frac{1}{2}(e_b(n)\right.\right.\\ & \left.\left. + e_b(n-1))\Delta t + Z(n-1)\right\}\right]\\ & + M \qquad \cdots(5)\end{aligned}$$

$$\begin{aligned}Z(n) = {} & \frac{1}{2}\{e_b(n) + e_b(n-1)\}\Delta t\\ & Z(n-1) \qquad \cdots(6)\end{aligned}$$

$$e_b(n) = N_{bo} - N_b(n) \qquad \cdots(7)$$

where K_{bp}: proportional gain,
T_{bI}: integral time,
$\theta_b(n)$: output in n times,
$e_b(n), e_b(n-1)$: speed error in n,n-1 times,
Δt: control sampling time,
N_{bo}: set blower speed,
$N_b(n)$: blower speed measured in n times.

The control equation is PI discrete control action. When the operator changes the set blower speed (N_{bo}) suddenly stepwise, (M) in the equation is the input of the static action point (N_{bo}) so that the setting time becomes fast.

The value of (M) was obtained by no load examinations. The values of the control parameters (K_{bp}) and (T_{bI}) were obtained as $K_{bp}=1$ and $T_{bI}=1$ by the simulations and no load examinations.

5-2 Clearing speed control

In the work of the snow clearing, it is necessary to keep the load against the snowplow constant so that the clearing speed becomes the maximum. Because the load of the rotary snowplow is the function of the clearing speed

(V) as shown in Eqs.(3) and (4). But as the load of the rotary snowplow can not directly measured cheaply, it is necessary for the controlled variable to replace the load. Here the engine revolution speed, the pump load pressure, the load power and the estimation load torque were considered.

(A) Engine speed control

Until now, the operator observed the fluctuation of the load by the a fluctuation of the engine revolution speed or a sound of the engine.

Consequently, although there is the governor, the engine revolution speed is controlled in order to keep the load constant. The proportional and the derivative control action were used as the control equation.

$$\theta_v(n) = K_{rp}\left\{e_r(n) + T_{rD}\frac{e_r(n)-e_r(n-1)}{\Delta t}\right\} + \theta_v(n-1) \quad \cdots(8)$$

$$e_r(n) = N_e(n) - N_{eo} \quad \cdots(9)$$

where T_{rd}: derivative time,
$N_e(n)$: engine speed measured in n times,
N_{eo}: set engine speed,
$\theta_v(n),\theta_v(n-1)$: control output in n,n-1 times,
$e_r(n),e_r(n-1)$: engine speed error in n,n-1 times

(B) Pump load pressure control

The response of the pump load pressure is faster than that of the engine speed. The derivative control action was not used, because the overall response speed was slow.

$$\theta_v(n) = K_{pp}\cdot e_p(n) + \theta_v(n-1) \quad \cdots(10)$$

$$e_p(n) = P_o - \{P_b(n) + R_{br}\cdot P_r(n)\} \quad \cdot(11)$$

where $e_p(n)$: pressure error in n times,
P_o: set load pressure,
$P_b(n)$: load pressure of clearing in n times,
$P_r(n)$: load pressure of running in n times,
R_{br}: ratio between pressure of clearing and running.

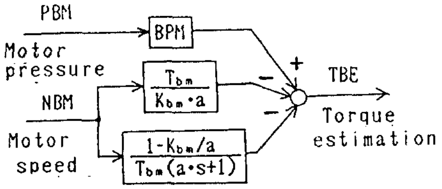

Fig.10 Block diagram of torque estimation.

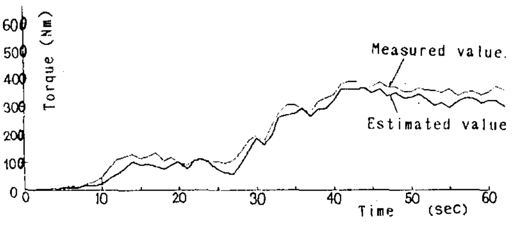

Fig.11 Comparison measured torque with estimated torque.

Table 2 Conditions of load power control.

Clearing conditions		Average clearing height	0.68 m
		Snow density	0.25 g/cm
		Clearing width	2.60 m
Control conditions		Sampling time	0.1 sec
	Blower	Set blower speed	300 r.p.m
		Proportional gain	1
		Integral time	1 sec
	Clearing	Set load power	118 Kw
		Proportional gain	0.02

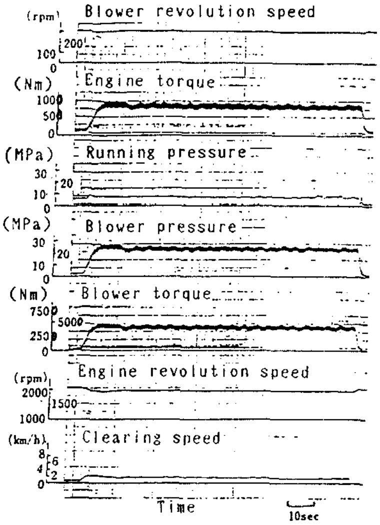

Fig.12 Experimental result of load power control.

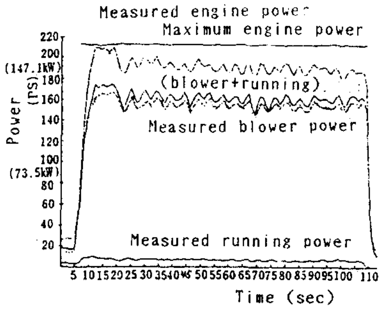

Fig.13 Time response of power.

(C) Load power control

As the load pressure and the revolution speed are simultaneously observed, the assumption of the load becomes accurately in the power.

$$\theta_v(n) = K_{hp}\cdot e_h(n) + \theta_v(n-1) \quad \cdots(12)$$

$$e_h(n) = H_o - \{H_b(n) + H_r(n)\} \quad \cdots(13)$$

where $e_h(n)$: power error in n times,
H_o: set load power,
$H_b(n)$: load power of clearing measured in n times,
$H_r(n)$: load power of running measured in n times.

Table 3 Conditions of load torque control.

Clearing conditions		Clearing height	0.3~1.2 m
		Snow density	0.35 g/cm
		Clearing width	0.5~2.6 m
Control conditions		Sampling time	0.1 sec
	Blower	Set blower speed	350 r.p.m
		Proportional gain	1
		Integral time	1 sec
	Clearing	Set engine speed	2000 r.p.m
		Proportional gain	1/120
		Set load torque	650 Nm

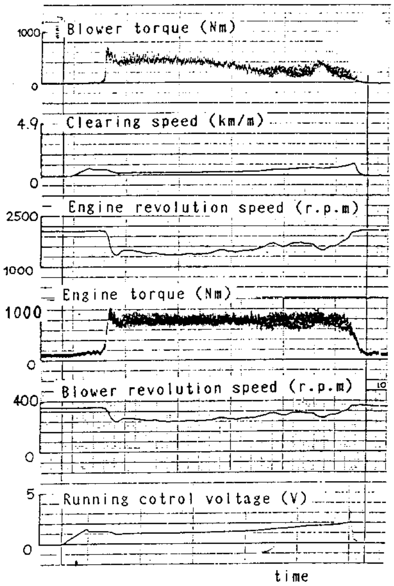

Fig.14 Experimental result of load torque control.

(D) Estimation load torque control

When the load torque is directly measured, the response of the load for the torque is faster and the toughness of the engine working may be possible. But the torque meter is expensive for the rotary snowplow. Consequently, we considered the estimation of the load for the clearing torque. The torque estimation was realized as Fig.10 from Fig.7. The comparison the torque estimation with the torque measured really is shown Fig.11. Both agreed well.

5-3 Experimental results and consideration

The control parameters in the each control equation were determined by the simulations.

The gain values in the each equation are about 0.01~0.02. One example of the experiment in the load power control is shown in Fig.12.

The condition of the snow clearing experiment is shown in Table 2 and the power response in the time process is shown in Fig.13. The control is stable. In addition, the objected balance which is distributed the engine power into the clearing power and the running power is good. About 80 % of the engine ability is made good use in the snow clearing. As the utilization in the manual operation is about 60~70 %, the improvement of the working efficiency is obtained very well. One example in the torque control is shown in Fig.14. The conditions of the snow clearing are shown in Table 3. As shown in Fig.14, the working operation which can not be realized by the other control methods is possible for the low engine revolution speed.

6. Conclusions

The set and control of the blower revolution speed compares well by the control equation shown in Eq.(5). When the running control and the blower speed control are simultaneously carried, the blower control system becomes the load of the running control system. Consequently, the work of the snow clearing in the suburbs in which the casting distance is not strict is good only by the running control.

Because the error of the set blower revolution speed is a little 5~6 r.p.m with only the running control. The clearing speed control was considered by the four methods. The results obtained are summarized as follows:

(1) Engine revolution speed control is most simple. But as the load is transferred the slowest, it becomes more unstable when the fluctuation of the load is large or fast.

(2) Load pressure control is more stable as the transmission of the load is faster than Engine revolution speed control. However the ratio between the clearing load pressure and the running load pressure is not constant with the road conditions.

(3) The set of the load power in Load power control can be most simply determined. But the number of measured variables is many, with four.

(4) The engine is operated with a toughness by Load torque control and it is more stable. The measured variables are the same four as the method of Load power control.

(5) Choosing from the above methods (1)~(4), Load power control or Load torque control are better than the others. An improvement in working efficiency is obtained by these methods.

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