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LOAD CONTROL OF A 300 h.p. TUNNELLING MACHINE:

THE ADDITION OF INTEGRAL CONTROL ACTION TO PREVENT MANUALLY CREATED OVERLOADS

by

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SUMMARY

Whereas a proportional-plus-derivative controller (designed in Research Reports 220 and 230) for the Cadley Hill tunnelling machine was shown to produce only small load errors in response to changes in rock hardness, errors resulting from excessive manual rate settings were not investigated. It is here proposed that effective integral action be incorporated to eliminate such errors, which can be excessive because of the very wide range of rate settings available to the driver. Implementations using a d.c. blocking circuit in the rate feedback channel of the N.C.B. controller are tested connected to the analogue simulator of the tunnelling machine and shown to be successful. Redesign of the existing printed circuits will, however, be necessary to achieve an overriding controller that is completely error free.

1. Introduction

This report is the third of a series (following Research Reports 220 and 230) concerned with improvements to the existing load control system applied to the 300 h.p. machine operating at Cadley Hill Colliery.

The transfer-function previously derived for the system is

$$\frac{P_i'}{v_r} = G_m(s) = \frac{(1-e^{-sT})k_2 k_h}{s(1+T_h s)(1+T_m s)(1+T_f s)} \qquad (1)$$

where

P_i' = measured value of electrical power P_i (in kW)

v_r = demanded speed of boom rotation

k_2 = 1/average motor and drive efficiency (set at 1.25)

k_h = rock hardness factor (set nominally at 3200 kw/m bite)

T = time between arrivals of successive cutting picks (set at 1.8s)

T_h, T_m and T_f = time constants of the hydraulic servo (set at 0.25s), the induction motor (set at 0.5s but later calculated at 0.048s) and the power transducer filter (considered to be negligible)

s = Laplace variable ($\equiv d/dt$)

The form of control proposed in Research Report 230 was simple proportional control of boom rotational speed v up to the point where P_i' exceeds preset load reference P_r whereupon derivative plus delayed proportional control of P_i takes over, i.e.

$$v_r = v_d + k_1\left\{ \frac{(P_r - P_i')}{(1 + T_L s)} - \frac{k_d T_d s P_i'}{(1 + T_d s)} \right\}, \; P_i' > P_r \qquad (2)$$

and v_r = manually adjusted constant, v_d i.e. the so called 'rate reference'

$, \; P_i' < P_r$ (3)

T_L and T_d being the time constants of the added lag and derivative circuitry respectively, their designed values being 0.75s and 0.15s respectively. k_1 is the overall controller gain (a value of 0.0003 m/s/kw giving critical stability in the absence of lag T_L and derivative action i.e. $k_d = o$). The best value for the derivative gain k_d was found to be 2.69, used in conjunction with $k_1 = 0.0003$ m/s/kw which now yields adequate stability without sacrificing speed of response.

[Equation (2) is readily derived by considering the total signal applied to the servo valve torque motor and integrating the result to obtain pump delivery, and hence speed v, as follows:

$$v = H \int_o^t \{k_R(v_d - v) - k_L(\text{load control})\}\,dt \qquad (4)$$

where H is the integrating gain of the open loop servo and k_R and k_L are the independent rate- and load-control channel gains. Hence in terms of Laplace transforms:

$$v(k_R + H^{-1}s) = k_R v_d - k_L(\text{load control})$$

so that $$v = \frac{v_d - (k_L/k_R)(\text{load control})}{1 + T_h s} \qquad (5)$$

where $T_h = (H\,k_R)^{-1}$ (6)

and $k_1 = k_L/k_R$ (7)

and, since $v = v_r/(1+T_r s)$ (8)

and the load control signal

$$= \frac{P_r - P'_i}{1+T_L s} - \frac{k_d T_d s\, P'_i}{1 + T_d s} \qquad (9)$$

equation (2) naturally follows].

1.1 Steady state performance

Using the original proportional controller, the steady-state operating load will vary from the load reference setting, P_r, by an amount depending on the rock hardness factor, k_h, (which varies with pick sharpness) and the controller gain k_1. The larger the value of k_1, the smaller will be this variation and, in the previous report (230), it was shown that, by including the compensator network, the controller could be operated in a stable manner with considerably larger values of k_1 than is possible with the existing, uncompensated controller. Indeed, k_1 could be increased such that, typically, with the compensator included, a 50% variation in rock hardness (or pick sharpness) causes only a 10% variation in steady-state load, compared to a 21% variation without the compensator.

The effect of increasing k_1 on the immunity of the load to variation in k_h is brought out by the following analysis which also demonstrates the effect of varying the manually set rate demand v_d:

Taking the steady state versions of equations (1), (2) and (3) we get respectively:

$$P_i' = k_2 k_h T v_r \tag{10}$$

$$v_r = v_d + k_1(P_r - P_i') = v_d + (k_L/k_R)(P_r - P_i') \quad , \quad P_i' > P_r \tag{11}$$

and

$$v_r = v_d \quad , \quad P_i' < P_r \tag{12}$$

and, from equation (8), in steady state

$$v = v_r \tag{13}$$

Eliminating v_r between equations (10) and (11) readily gives

$$P_i' = \frac{k_R v_d + k_L P_r}{k_R (k_2 k_h T)^{-1} + k_L} = \frac{v_d + k_1 P_r}{(k_2 k_h T)^{-1} + k_1} \quad = P_i' > P_r \tag{14}$$

(i.e. on load control)

and from (10) and (12)

$$P_i' = k_2 k_h T v_d \quad , \quad P_i' < P_r \tag{15}$$

(i.e. on rate control)

1.1.1 Sensitivity to Rock Hardness and Pick Sharpness Changes

It is obvious from equation (14) that the sensitivity of P_i' to variation k_h is reduced by increasing the ratio k_L/k_R ($=k_1$) as previously observed. In fact, differentiating P_i' partially with respect to k_h, in equation (14) gives the following sensitivity function for the ratio of % power: % hardness change, i.e.:

$$\frac{\partial P_i'/P_i}{\partial k_h/k_h} = \frac{1}{1+k_1 k_2 k_h T} \qquad (16)$$

For the assumed values of k_2 = 1.75, k_h = 4800 kw/m bite and T = 1.8s, equation 16 yields values for the sensitivity function of 1/4.24 @ k_1 = 0.0003 m/s/kw (i.e. for the compensated controller) and only 1/2.62 with k_1 reduced to 0.00015 (i.e. the value necessary to adequately stabilise the existing uncompensated controller). Both results clearly accord closely with the observed load variations mentioned previously.

1.1.2 Sensitivity to Rate Reference Changes

At a given load reference setting, P_r, and operating under conditions of constant k_r it is clear from equations (14) and (15) that P_i' will vary with varying v_d according to

$$\frac{\partial P_i'}{\partial v_d} = k_2 k_h T \quad , \qquad P_i' < P_r \text{(i.e. on rate control)} \qquad (17)$$

and

$$\frac{\partial P_i'}{\partial v_d} = \frac{k_2 k_h T}{1+k_1 k_2 k_h T} \quad , \qquad P_i' > P_r \text{(i.e. on load control)} \qquad (18)$$

The sensitivity of P_r to of v_d is illustrated in Fig. 1. Ideally this sensitivy should be zero for $P_i' > P_r$ but with the existing form of controller some sensitivity will remain between the load and the rate reference setting even on load control. Adding the compensator has the advantage that k_1 can be considerably increased, so reducing the sensitivity but, because the change in v_d available to the driveris so large, the resulting change in P_i' remains considerable, Specifically, assuming $v_{d\,max}$ = 5x $P_r/k_2 k_h T$

(i.e. 5 times the speed at which load control takes over), then, from equations 17 and 18, the effect of the driver setting $v_d = v_{d\ max}$ would be to increase the load by

$$\Delta P_i' = \frac{k_2 k_h T \Delta v_d}{1+k_1 k_2 k_h T}$$

$$= \frac{4 P_r}{1+0.0003\ 1.25\ 3200\ 1.8} = \frac{4 P_r}{3.16} = 1.27 P_r$$

i.e. the load would rise to 2.27x the setting of the load reference. Using the lower value of k_1 (0.00015) appropriate to the uncompensated controller, the load would rise to 2.92 x P_r.

These observations are confirmed by actual simulation and it follows that, whereas the compensator copes very well with hardness and sharpness changes, and eliminates low frequency load oscillation, it is not foolproof in protecting against erronious setting of the driver's rate reference.

2. Integral Control Action for Zero Steady-State Error

Steady state errors due to variation in k_h or v_d are readily eliminated in principle by the addition of some integral control action in which a term $k_i \int (P_r - P_i')dt$, where k_i is the integral gain, is added to the R.H.S. of control law (2), taking care to properly initialise the integrator. While ever any error between P_r and P_i' exists, for whatever cause, the integrator output winds up (or down) to offset this cause and so eliminate the error. Too large a value of k_i will destabilise the system however and this parameter must be set with care.

2.1 Transient Valocity Realisation

A somewhat simpler realisation can be effected by blocking the rate error signal $v_d - v$ in steady state by means of a suitably chosen capacitor inserted directly in this feedback path. In steady state therefore only the power error acts on the servo valve and the hydraulic integration of the system thus eliminates the error. The system thus becomes a true load controller and not a composite load and speed controller such as pertains at present when P_r is exceeded.

The principle was tested by insertion of a blocking capacitor C_B initially in the speed feedback path as shown in Fig. 2 and as expected, the error due to changes in k_h were eliminated as the results of Section 3 reveal. Later the capacitor was transferred to the output of rate potentiometer RV8 in Fig. 2 to eliminate any steady state effects from the rate demand setting: again successfully as expected.

Unfortunately, without adding extra integrated circuits and extensive printed circuit redesign, the controller could now only be operated as a continuous load controller because the rate amplifier IC - 2 (761) also processes the derivative feedback so precluding the addition of a diode across the blocking capacitor (such a diode being necessary to by-pass the capacitor when pure rate-control is operative).

The size of the blocking capacitor was calculated as follows:

Frequency of oscillation to be stabilised, $\omega_c \simeq 2\pi 0.3$

$\simeq 2.0$ rad/s

Blocking circuit transfer function = $T_B s/(1+T_B s)$

where time constant $T_B = C_B R_{16} >> 1/\omega_c$ (to avoid interference in the critical frequency range)

$\therefore$ Make $T_B = 10/\omega_c$, $R_{16} = 10$ kΩ

so that $C_B = 10/R_{16}\,\omega_c = 10/10^4 2$ F

i.e. $C_B = 500\ \mu F$

A range of values in this region were investigated and results are given in Section 3.

3. Results

Figs. 3 and 4 shows the behaviour of the existing controller with the compensator (RR220 and 230) added plus a blocking capacitor C_B in the rate feedback signal (from the simulated pump transducer). Step responses to switch-on, 50% decrease and 50% increase in rock hardness are shown, for the following operating conditions and parameter settings (as were used in RR230):

$k_h = 3200 \rightarrow 1600 \rightarrow 4800$ kw/m bite	Load = 60%
$T = 1.8$s	Rate = 27%
$k_2 = 1.25$	Derivative = 80%
$T_m = 0.5$s	Gain (hydraulic) = 10%
effective $P_r = 120$ kw	$C_L = 69$ μF, $C_D = 30$ μF.

The blocking capacitor C_B used was 470 μF for Fig. 3 and only 100 μF for Fig. 4 (compared to the theoretically estimated value of 500 μF). In comparing these traces with Fig. 10 of RR 230 it is obvious that, as expected, the load error due to hardness change is now eliminated completely. The rate at which the state error is eliminated in Fig. 3 is clearly slower than in Fig. 4 (due to the larger value of C_B used for Fig. 3) but rather more oscillation is induced in Fig. 4. A value of C_B around 500 μF would therefore seem to be preferable.

Fig. 5 shows the effect of inserting a C_B of 470 μF in the output of the rate error potentiometer RV8 which, in the preliminary implementation, also processes the derivative power feedback signal. Never-the-less the transient performance remains good and again, as expected, the static power error is completely eliminated. (i.e. P_i' is restored to the P_r setting of 95 kw in this case). Experiments showed that, as expected, adjustment of the drivers rate demand potentiometer caused no steady-state alteration of the running load.

4. Conclusions

It has been shown by modification of the existing machine controller and coupling this to the tunnelling machine simulator that steady-state load errors can be completely eliminated by the addition of a 500 μF blocking capacitor in the rate feedback channel (assuming a 10 kΩ input resistor). This provides a means of eliminating the possibility of the driver inadvertently overloading the machine (in overriding control mode) by setting an excessive rate-demand signal: the blocking capacitor in the rate error channel completely blocking this source of error in steady state whilst allowing the transient stabilising function of rate feedback to operate as before.

Unfortunately, because of constraints on the number of integrated circuit amplifiers in the existing controller it is not possible at present to isolate the rate-error channel completely from the derivative power feedback. This causes complications in operating the system as an error-free overriding load controller and some redesign of the printed circuit boards to accommodate extra integrated circuit amplifiers for isolating the separate signal channels may well be necessary before this final objective can be achieved. This redesign is under discussion with Dowty Systems Ltd.

5. References

(1) Edwards, J.B. "Load Control of a 300 h.p. tunnelling machine" University of Sheffield, Control Eng. Research Report 220, April 1983, 23 pp.

(2) Edwards J.B. and Sadreddini S.M. "Load control of a 300 h.p. tunnelling machine: Controller modification and testing for underground trials" University of Sheffield, Control Eng. Research Report 230, June 1983, 23pp.

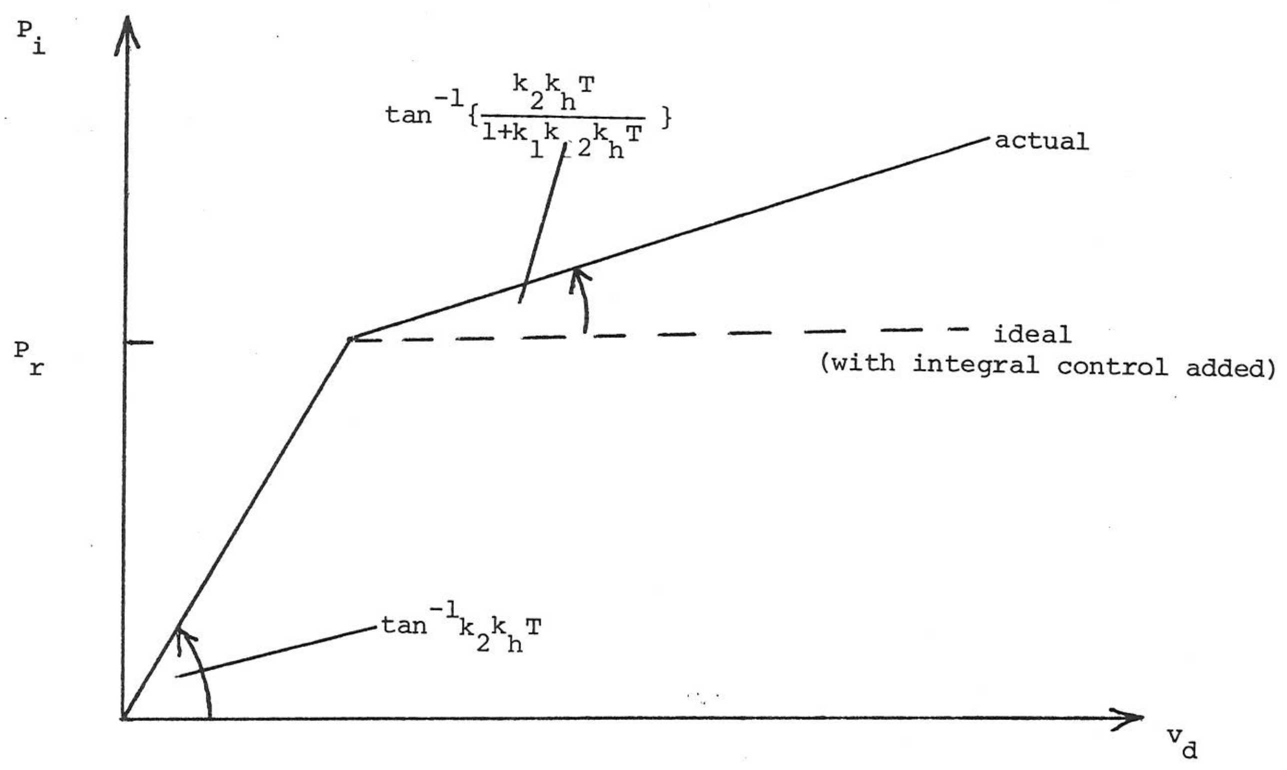

Fig. 1: Showing relationship between input power P_i and drivers' rate-reference setting v_d with existing form of controller

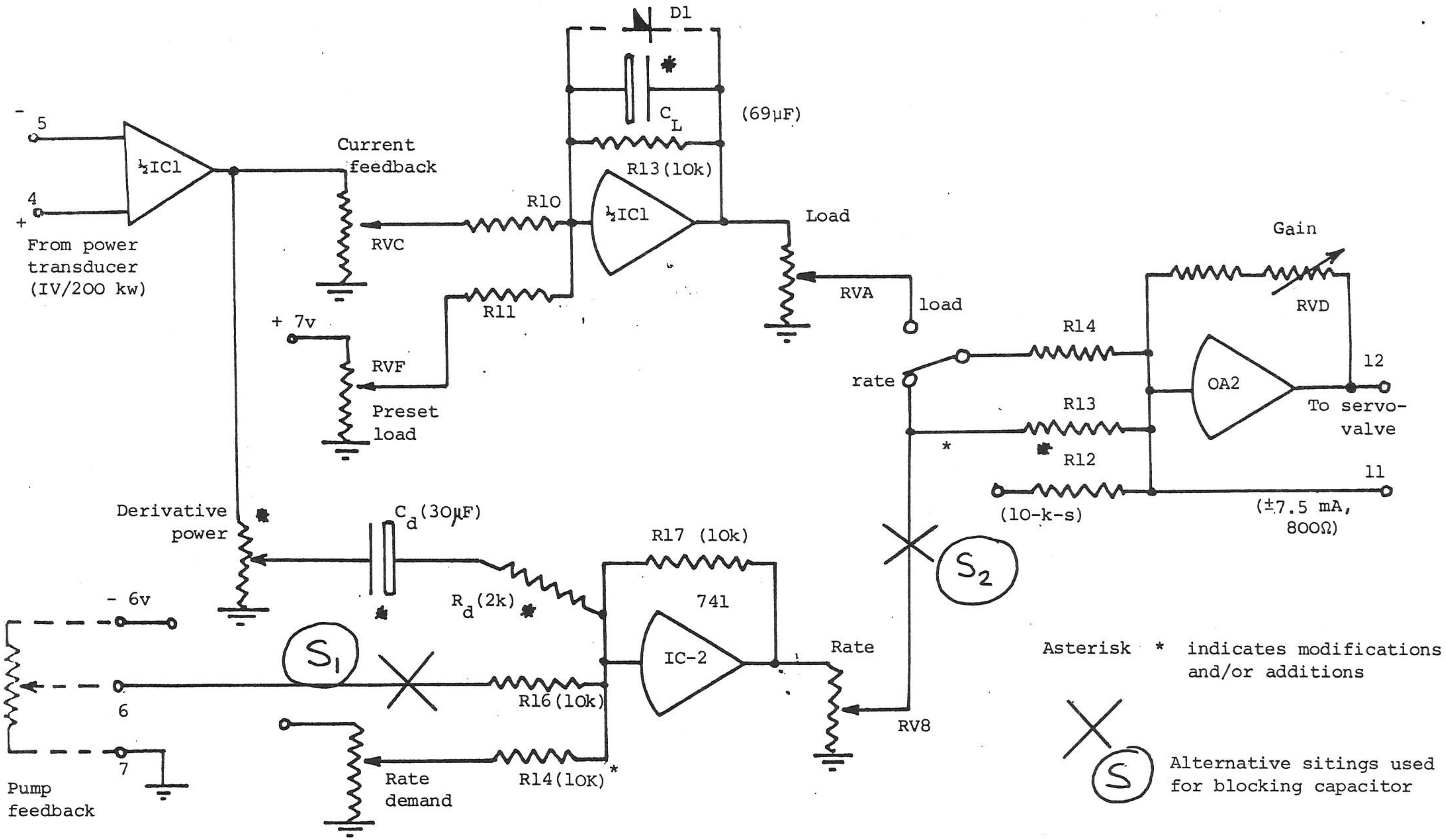

Fig. 2 Modified N.C.B. control amplifier (MRDSK 15392) showing sitings for d.c. blocking capacitor

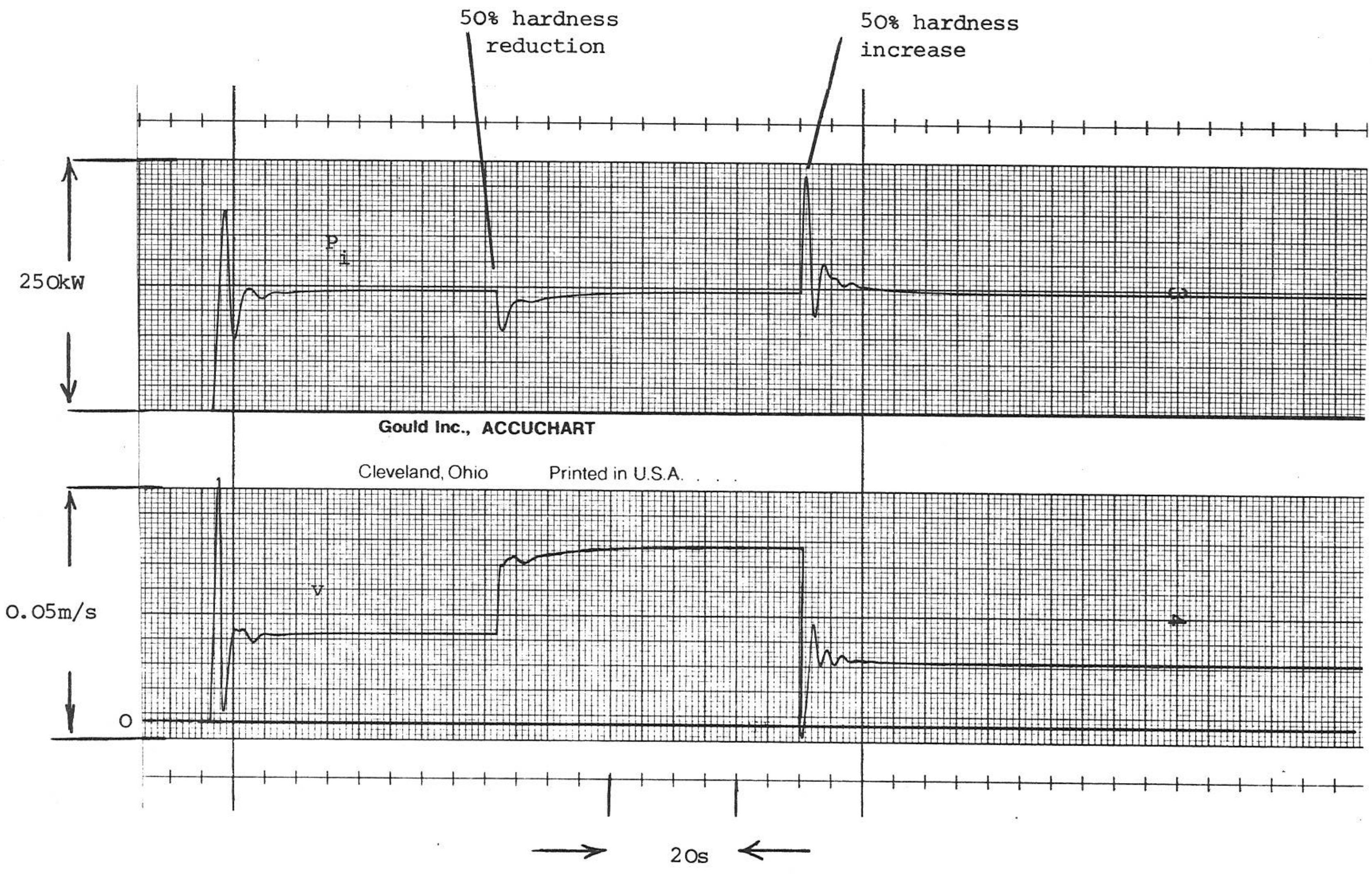

Fig. 3 Responses of compensated system @ 80% derivative feedback with 470 μF blocking capacitor in pump feedback

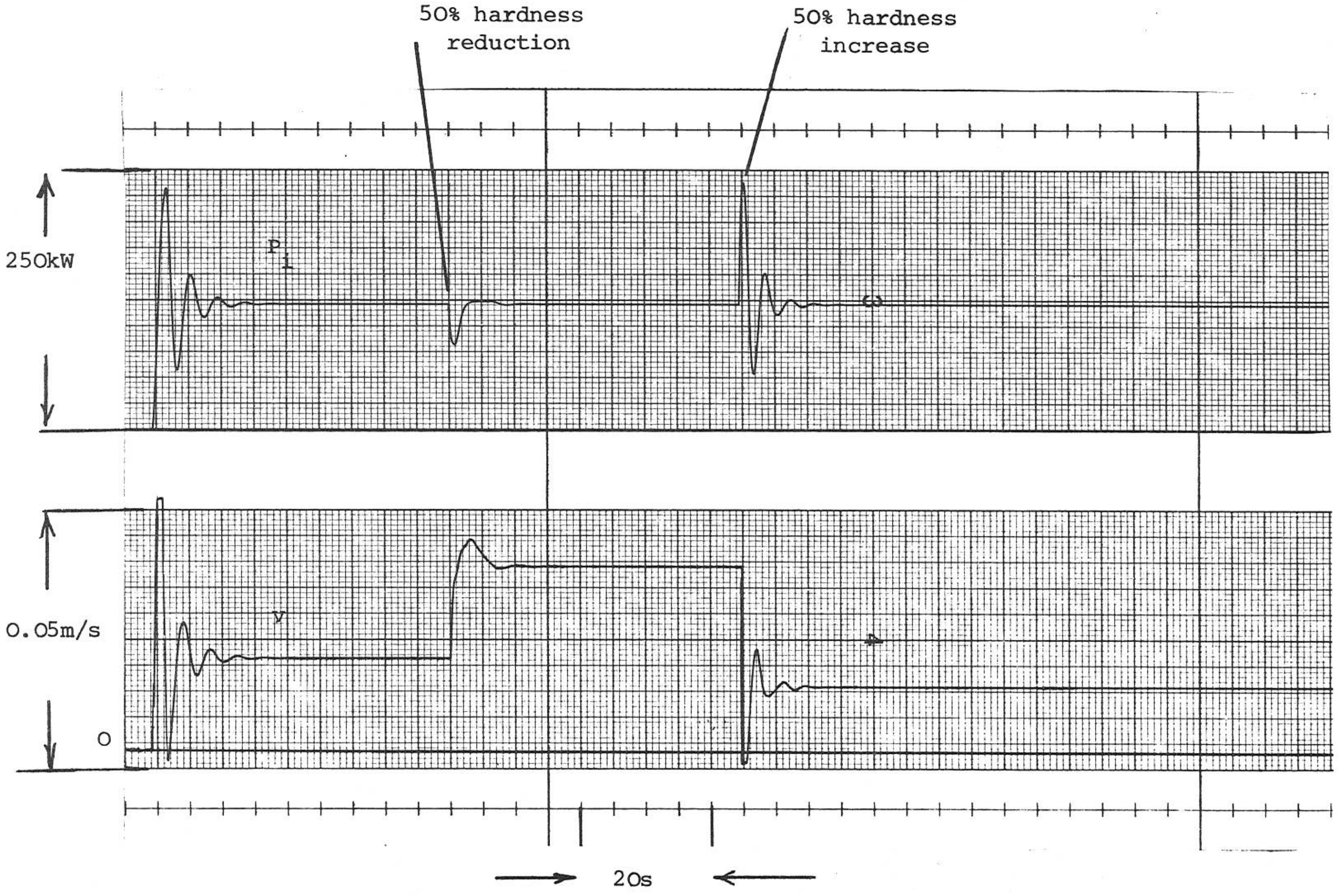

Fig. 4 Responses of compensated system @ 80% derivative feedback with 100 μF blocking capacitor in pump feedback

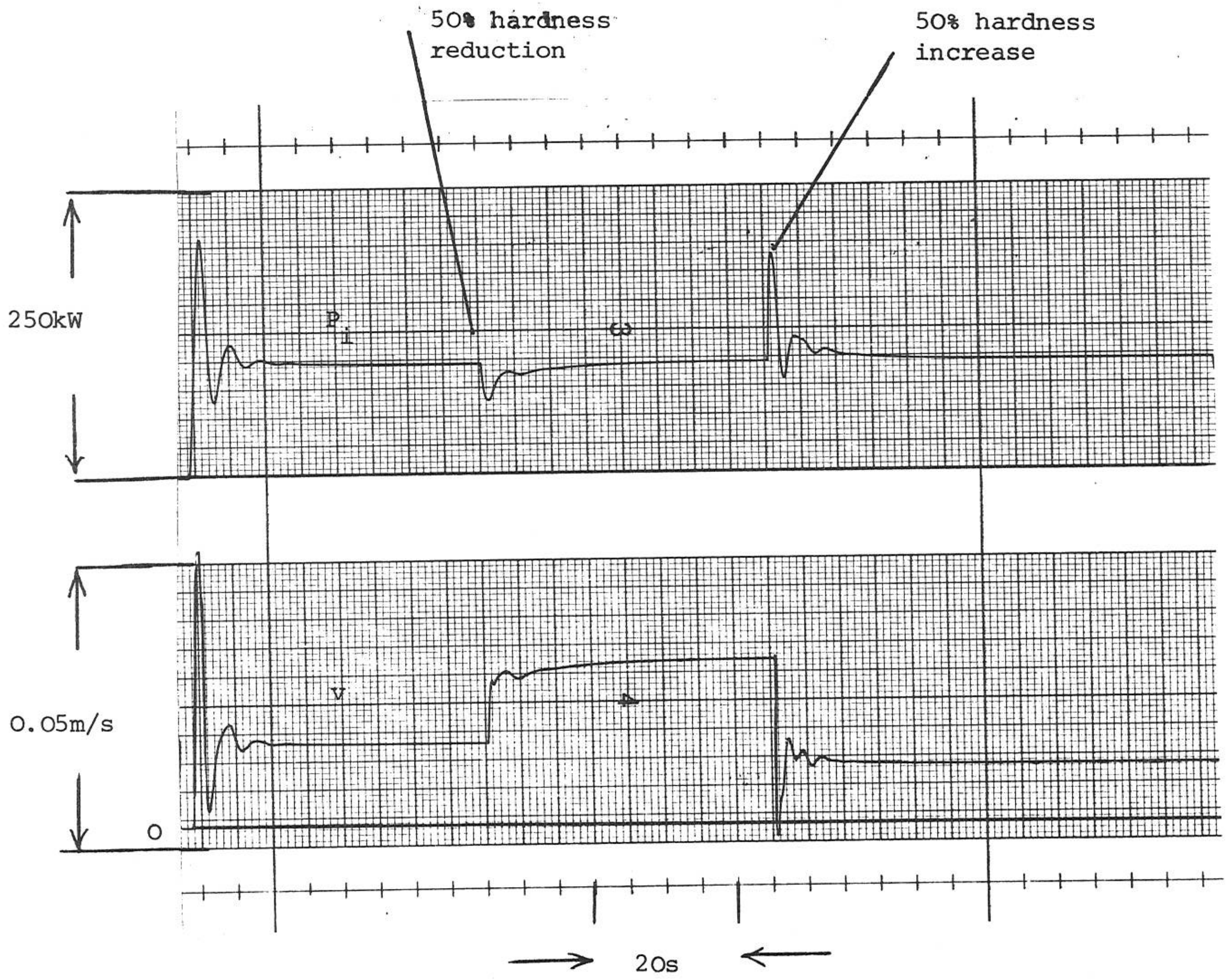

Fig. 5 Responses of compensated system @ 80% derivative feedback with 470 µF blocking capacitor in output of rate error amplifier