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LOAD CONTROL OF A 300 h.p. TUNNELING 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

\[
\frac{P'_i}{v_r} = G_m(s) = \frac{(1-e^{-sT})k_2k_h}{s(1+T_h)(1+T_m)(1+T_f)}
\]

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.

\[
v_r = v + k_1 \left\{ \frac{(P_r - P'_i)}{(1 + T_L)} - \frac{k_2T_dsP'_i}{(1 + T_d)} \right\}, \quad P'_i > P_r
\]

and \( v_r \) = manually adjusted constant, \( v_d \) i.e. the so-called 'rate reference', \( P'_i < P_r \)
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. \( k_d = 0 \)). 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:

\[
 v = \frac{H}{k} \int_0^t \left( k_R (v_d - v) - k_L (load \ control) \right) \, dt
\]

(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:

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

so that

\[
v = \frac{v_d - (k_L/k_R) (load \ control)}{1 + \frac{T_h}{s}}
\]

(5)

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

and \( k_1 = k_L/k_R \)

(6)

(7)

and, since \( v = \frac{v_x}{(1+T_x s)} \)

and the load control signal

\[
 = \frac{P - P'}{l + T_L s} - \frac{k_d T_s P'}{l + T_d s}
\]

(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:

\[
P'_i = k_2 k_h \frac{T}{R} v_r
\]

\[
v_r = v_d + k_1 (P - P'_i) = v_d + \left(\frac{k_r}{k_u} \frac{1}{R} \frac{1}{L} \right) (P - P'_i), \quad P'_i > P_r \quad (10)
\]

and

\[
v_r = v_d, \quad P'_i < P_r \quad (12)
\]

and, from equation (8), in steady state

\[
v = v_r
\]

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

\[
P'_i = \frac{k_R v_d + k_L P_i}{k_R (k_u k_h T)^{-1} + k_L (k_u k_h T)^{-1} k_1} = \frac{v_d + k_1 P_i}{k_R (k_u k_h T)^{-1} + k_L (k_u k_h T)^{-1} k_1}
\]

\[
= P'_i > P_r \quad (i.e. \ on \ load \ control) \quad (14)
\]

and from (10) and (12)

\[
P'_i = k_2 k_h \frac{T}{R} v_d, \quad P'_i < P_r \quad (i.e. \ on \ rate \ control) \quad (15)
\]

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 the power: the hardness change, i.e.:

$$\frac{3P_i'/P_i}{3k_h/k_h} = \frac{1}{1+k_1 k_2 h T}$$

(16)

For the assumed values of $k_2 = 1.75$, $k_h = 4800$ kw/m bite and $T = 1.8$s, 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

$$\frac{3P_i'}{3v_d} = k_2 k_T$$

(17)

$$P_i' < P_r (\text{i.e. on rate control})$$

and

$$\frac{3P_i'}{3v_d} = \frac{k_2 k_T}{1+k_1 k_2 h T}$$

(18)

$$P_i' > P_r (\text{i.e. on load control})$$

The sensitivity of $P'_{r}$ to of $v_d$ is illustrated in Fig. 1. Ideally this sensitivity 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 driver is so large, the resulting change in $P_i'$ remains considerable. Specifically, assuming $v_{d\text{ max}} = 5x P_r/k_2 k_T$
(i.e. 5 times the speed at which load control takes over), then, from
equations 17 and 18, the effect of the driver setting \( v_d = v_{d\text{ max}} \) would
be to increase the load by

\[
\Delta P'_1 = \frac{k_c k_r T \Delta v_d}{1 + k_c k_r T} = \frac{4 P_r}{1 + 0.0003 \times 1.25 \times 3200 \times 1.8} = \frac{4 P_r}{3.16} = 1.27 P_r
\]

i.e. the load would rise to 2.27\( x \) 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 erroneous 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 elimi-
nated in principle by the addition of some integral control action in which
a term \( k_1 \int (P_r - P'_1) dt \), where \( k_1 \) 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 \( P'_1 \) 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 \( k_1 \) will destabilise the system however
and this parameter must be set with care.

2.1 Transient Velocity 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, \( \omega_c = 2 \pi 0.3 \)

\[ \approx 2.0 \text{ rad/s} \]

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

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

\[ \therefore \text{ Make } T_B = 10/\omega_c \quad R_{16} = 10 \text{ k}\Omega \]

so that \( C_B = 10/R_{16} \omega_c = 10/10^4 \approx 2 \text{ F} \)

\[ \text{i.e. } C_B = 500 \mu\text{F} \]

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

Figs. 3 and 4 show 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):

$$k_h = 3200 + 1600$$

$$\rightarrow 4800 \text{ kw/m bite}$$

$$T = 1.8s$$

$$T_m = 0.5s$$

$$k_2 = 1.25$$

$$\text{effective } P_x = 120 \text{ kw}$$

$$\text{Load} = 60\%$$

$$\text{Rate} = 27\%$$

$$\text{Derivative} = 80\%$$

$$\text{Gain (hydraulic)} = 10\%$$

$$C_L = 69 \mu F, C_D = 30 \mu F.$$  

The blocking capacitor $C_B$ used was 470 $\mu F$ for Fig. 3 and only 100 $\mu F$ for Fig. 4 (compared to the theoretically estimated value of 500 $\mu F$).

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 $\mu F$ would therefore seem to be preferable.

Fig. 5 shows the effect of inserting a $C_B$ of 470 $\mu F$ in the output of the rate error potentiometer RV8 which, in the preliminary implementation, also processes the derivative power feedback signal. Nevertheless the transient performance remains good and again, as expected, the static power error is completely eliminated. (i.e. $P'_1$ is restored to the $P_x$ 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**


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