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COPY NO. 124

DATE: April 4, 1958

SUBJECT: Frequency Response Analysis of the HRT Feedwater Control System

TO: Distribution

FROM: S. J. Ball

SUMMARY

A frequency response analysis is made of the HRT fuel feed-water system. The characteristics of the components are determined and used in the differential equation of the system. Using frequency response techniques, theoretical calculations of static and dynamic response characteristics are made for reactor operation at 5 megawatts. The conclusions arrived at as a result of this analysis include suggestions for improving the present operation.

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FREQUENCY RESPONSE ANALYSIS OF THE HRT FEEDWATER CONTROL SYSTEM

Introduction

The HRT fuel feedwater control system, shown in Fig. 1, consists of a 1000 psi constant pressure water supply¹, a Hammel-Dahl control valve with positioner, a Foxboro d/p cell level detector, and a Foxboro model M58 controller. The purpose of the system is to keep the water level in the heat exchanger above the tubes and below the dry box. Any deviation of the water level from the control point produces an error signal in the controller. The controller then transmits a signal which re-positions the valve. The resultant change of flow rate into the heat exchanger then tends to restore the level back to the control point.

Fig. 1

HRT FEEDWATER CONTROL SYSTEM SCHEMATIC DIAGRAM

It is felt that control conditions for the blanket feedwater system are much less severe than those of the fuel feedwater system. Consequently, this analysis should suffice for both.

In this, as in any "closed loop" control system, a compromise must be made between accuracy and stability. A "tight" or high gain control loop is generally very sensitive to small input changes and noise. Although such a system would be capable of controlling the water level very closely, there are two reasons why it would be

unsatisfactory: (1) Very small error signals, either true signals or noise, would cause large changes in the valve position, producing a chattering or oscillating valve action; and (2) the fast changes in the flow rate requirements would overburden the water supply, which could then no longer be considered a constant pressure source.

On the other hand, even though a "loose" or low gain system would not oscillate or overload the water supply, it may not be able to maintain the water level within tolerances for extreme load changes.

It is the purpose of this study to find a compromise point between the two extremes, and to predict the static and dynamic operating characteristics of the control system.

Assumptions

The following assumptions must be made in order to make a reasonably simple analysis. It is felt that the errors they introduce are not significant.

1. Valve operation is linear around a given operating point.
2. Pressure drops in piping are negligible.
3. Feedwater inlet pressure is constant (1000 psi).
4. Effects of water temperature changes on level indication or calculations are insignificant. (The feedwater inlet temperature is 210°F.)
5. Frequency response of the transmitter (D/P cell) is constant over the region of interest.

Component Characteristics

1. The controller has adjustable gain and reset action. Its transfer function (H_1) will be determined later.

2. Valve LCV-545 Characteristics

$$C_v (\text{max.}) = 6.3 \text{ (linear)}$$

$$\text{INPUT} = 3\text{-}15 \text{ psi air}$$

$$\Delta C_v = \frac{(\Delta \text{psi air})}{12} \times C_v (\text{max.}) = .525 \times (\Delta \text{psi air})$$

At 5 MW reactor power, the pressure in the heat exchanger = 520 psi.

The pressure drop P across the valve = 1000-520 = 480 psi

The change in flow through the valve $\Delta Q = \Delta C_v \sqrt{P}$ gpm

$$\Delta Q = (.525) \sqrt{480} \times (\Delta \text{psi air})$$

The valve zero frequency gain is

$$\frac{\Delta Q}{\Delta \text{ psi air}} = 11.5 \frac{\text{gpm}}{\text{psi}}$$

Experimental measurement of the frequency response of a similar valve and positioner indicates a single linear lag at 8.8 cpm or 55 radians/min.

Hence

$$H_2 = \frac{11.5}{\frac{1}{55s} + 1} = \frac{11.5}{.018s + 1} \frac{\text{gpm}}{\text{psi}}$$

where s is the Laplacian operator, and H_2 is the transfer function of the valve.

3. Heat Exchanger Vessel Characteristics

Surface area at the desired control level = 25.8 ft²

$$\text{Sensitivity} = \frac{25.8}{12} \frac{\text{ft}^2}{\text{in/ft}} \times 7.481 \frac{\text{gal}}{\text{ft}^3} = 16.1 \frac{\text{gal}}{\text{in.}}$$

$$Q_s = \text{Rate of storage} = 16.1 \frac{\text{gals}}{\text{in.}} \times \frac{dL}{dt} \frac{\text{in.}}{\text{min.}} = 16.1 \text{ sL gpm}$$

where L = change in level in inches.

The expression for a change in level is

$$H_3 = \frac{L}{Q_s} = \frac{1}{16.1 \text{ s}} = \frac{.062}{s} \frac{\text{in.}}{\text{gpm}}$$

where H_3 is the vessel transfer function.

4. D/P Cell Characteristics

Range = 0-28" H₂O

Output = 3-15 psi air

The measurement gain of the transmitter is therefore

$$H_4 = \frac{12}{28} = .429 \frac{\text{psi}}{\text{in.}}$$

Fig. 2. Open Loop Response of HRT Fuel Heat Exchanger Feedwater Control System. Operation at Five Megawatts.

Open Loop Equation

The open loop equation for the entire system can now be written as $H =$

$H_1 \cdot H_2 \cdot H_3 \cdot H_4$, where H represents the ratio of the pressure signal of the d/p cell to a sinusoidal pressure input to the controller.

$$H = H_1 \times \frac{11.5}{.018s + 1} \frac{\text{gpm}}{\text{psi}} \times \frac{.062}{s} \frac{\text{in.}}{\text{gpm}} \times .429 \frac{\text{psi}}{\text{in.}}$$

$$H = \frac{.306 H_1}{s(.018s + 1)} \frac{\text{psi}}{\text{psi}}$$

The open loop characteristics of the system without the controller ($H_1 = 1$) are shown in Fig. 2a.

The active surface of the water in heat exchanger causes the level measuring signal to be inherently noisy. Therefore, it is advisable to attenuate the resultant high frequencies in the d/p cell output. To do this, a Taylor single-unit pulsation damper should be inserted in the pneumatic line between the d/p cell and the controller. Tests of such a damper have indicated the presence of a single linear lag at 17 cpm or 107 radians per minute. The damper transfer function is then:

$$H_5 = \frac{1}{.0094s + 1} \frac{\text{psi}}{\text{psi}}$$

and the system equation becomes

$$H' = \frac{.306}{s(.018s + 1)(.0094s + 1)} \quad (\text{See Fig. 2b})$$

A block diagram of the entire system is shown in Fig. 3.

Figure 3

HRT FEEDWATER CONTROL SYSTEM BLOCK DIAGRAM

A typical design criterion for efficient and stable operation is that the system should have a 45° phase margin.³ This means that the open loop phase is $(-2\pi + \text{phase margin}) = -135^\circ$ for the frequency at which the gain is unity. The controller gain can be adjusted to give the desired phase margin. From Fig. 2b, it can be seen that the controller gain for the system with the pulsation damper should be about 100, and the crossover frequency (where gain = 1) is 5 cpm.

The reset action on the M58 controller is adjustable from .05 to 50 minutes per repeat, and the reset gain is 200. It is desirable to set the reset rate as high as possible in order to minimize overshoot at startup. However, from a stability viewpoint, the reset should be set at a low enough frequency so as not to contribute significantly to the critical phase lag. A good compromise point is a one minute per repeat setting.

The transfer function of the controller can then be written as:⁴

$$H_1 = \frac{20,000 (s + 1)}{(200s + 1)} \frac{\text{psi}}{\text{psi}} \quad \text{and the entire system as}$$

$$H'' = \frac{6120(s + 1)}{s(200s + 1)(.018s + 1)(.0094s + 1)} \frac{\text{psi}}{\text{psi}}$$

Fig. 4a shows the Bode plot of H'' .

A plot of the closed loop frequency response of the system is derived from the use of the Black-Nichols Chart (Fig. 5) and is plotted as Fig. 4b.

From the closed-loop diagram it can be seen that the system has a low frequency gain of 1.00, indicating that there will be no offset in level due to a set point change. Since the phase plot crosses the 180° lag line at 15 cpm, a high frequency level signal disturbance could cause damped oscillations at approximately this frequency. However, because the gain value is never much more than 1.0, such oscillations will be negligible.

In calculating the static and dynamic responses of a system, it is customary to apply a step function input or load change and observe the reaction. The open loop equation considers the input to be a level signal. Hence, a step input would represent an instantaneous level change or a controller set point change. A more pertinent characteristic of this system would be its response to a step change in reactor power level, which is equivalent to a step change in the flow rate out of the heat exchanger. In order to determine this characteristic, the block diagram of the system should be rearranged. Figure 6 shows the input variable as flow and the output as a level signal.

Fig. 4. HRT Fuel Heat Exchanger Feedwater Control System. Frequency Response Diagrams for Entire System. Operation at 5 megawatts.

Fig. 5. HRT Feedwater Control System. Black-Nichols Chart Derivation of Closed-Loop Frequency Response.

FIG. 6
HRT FEEDWATER CONTROL SYSTEM
BLOCK DIAGRAM REARRANGED FOR ANALYSIS

The closed loop equation for the ratio of output level to input flow is:⁵

$$\frac{C}{R} = \frac{H_3 H_4 H_5}{1 + H_1 H_2 H_3 H_4 H_5} \frac{\text{psi}}{\text{gpm}}$$

For a unit step function input, $R = \frac{1}{s}$, so the output

$$C = \frac{\frac{1}{s} \left[\frac{.062}{s} \right] \left[.429 \right] \left[\frac{1}{.0094s + 1} \right]}{1 + \frac{20,000(s + 1)(11.5)(.062)(.429)}{(200s + 1)(.018s + 1)(s)(.0094s + 1)}} \text{ psi}$$

$$C = \frac{\frac{.0265}{s^2 (.0094s + 1)}}{1 + \frac{6120(s + 1)}{s(200s + 1)(.018s + 1)(.0094s + 1)}} \text{ psi}$$

Since a mathematical reduction of this equation would be rather unwieldy, a graphical solution is used and is shown in Fig. 7. The output is then

$$C \approx \frac{4.3 \times 10^{-6} (200s + 1)}{s(s + 1)(.029s + 1)(.0094s + 1)} \text{ psi}$$

Fig. 7.

Fig. 8. HRT Feedwater Control System. Level Response to a 1gpm Step Change in Flow Out of Exchanger. Operation at 5 megawatts.

After undergoing a partial fraction expansion, the level signal takes the form

$$C = \frac{4.3 \times 10^{-6}}{s} + \frac{8.9 \times 10^{-4}}{s + 1} - \frac{13.0 \times 10^{-4}}{s + 34} + \frac{4.1 \times 10^{-4}}{s + 107} \text{ psi}$$

and in time varying form, expressed in inches:

$$C(t) = 1.0 \times 10^{-5} + 2.1 \times 10^{-3} e^{-t} - 3.1 \times 10^{-3} e^{-34t} + 1.0 \times 10^{-3} e^{-107t} \text{ inches}$$

As shown in Fig. 8, the maximum level deviation per gpm load change is about .002 inches. Since actual load changes would not be more than 10 gpm and not as severe as step functions, it can be seen that the system is theoretically capable of controlling level very closely. Because level deviations of the order of one inch are tolerable, it is suggested that the controller sensitivity be reduced from 100 to 10.

The equations for operation at any point between 0 and 10 megawatts differ only by a gain factor of less than 4. Thus, the resultant control characteristics are not significantly affected by changes in operating points.

Pen Response to Level Change

The addition of a pulsation damper between the d/p cell level detector and the recorder will make the pen response less sensitive to rapid level changes. Since operation of the blowdown valve on the heat exchanger will cause a fast drop in level, it is desirable to know how well the pen indication will follow the actual level.

The case for which the blowdown valve is wide open is considered. Since the compensating effect of the control system is negligible compared to the blowdown rate, only the level indication system, shown in Fig. 9, is analyzed.

The transfer functions of the d/p cell and pulsation damper were found to be

$$H_4 = .429 \frac{\text{psi}}{\text{in.}} \quad \text{and} \quad H_5 = \frac{1}{.0094s + 1} \frac{\text{psi}}{\text{psi}}, \text{ respectively.}$$

With s in radian/sec.,

$$H_5 = \frac{1}{.56s + 1} \frac{\text{psi}}{\text{psi}}$$

The measurement gain of the level indicator =

$$H_6 = \frac{28 \text{ in.}}{12 \text{ psi}} = 2.33 \frac{\text{in.}}{\text{psi}}$$

The change in level for the blowdown valve wide open is 1/3-in./sec., or $L = \frac{1}{3}t$.

In Laplacian form, $L = \frac{1}{3s^2}$.

Level indication (I) = Actual level (L) $\cdot H_4 \cdot H_5 \cdot H_6$

$$I = \left[\frac{1}{3s^2} \right] \left[.429 \right] \left[\frac{1}{.56s + 1} \right] \left[2.33 \right] = \frac{.333}{s^2(.56s + 1)}$$

After partial fraction expansion, the indication becomes

$$I = \frac{.333t}{s^2} = \frac{.205}{s} + \frac{.205}{(s + 1.7)}$$

In time varying form

$$I(t) = .333t - .205 + .205^{-1.7t}$$

As shown in Fig. 10, the pen indication follows the actual level very closely, the maximum error being about 0.2 inches.

Conclusions

It has been found that the fuel feedwater control system is satisfactory for operating conditions between 0 and 10 megawatts of reactor power.

The following suggestions are made for improving upon the present operation:

1. Add a single unit Taylor pulsation damper in the line between the d/p cell and the controller.
2. Set the controller gain at 10 (proportional band = 10%) and the reset at 1 minute per repeat.

Fig. 10. HRT Core Heat Exchanger Level Indicator with one Taylor Pulsation Damping Unit in Line to Indicator. Pen Response to Level Change with Blowdown Valve Wide Open.

The addition of the pulsation damper has no appreciable effect on the recorder pen response.

References

1. See "HRT Steam System Feedwater Pressure Control" by H. D. Wills, CF Memo 58-4-8, April 15, 1958
2. See M.I.T. Practice School report EPS-X-272, KT-240, Fig. 15, R. Gelman and C. S. Robertson, Jr., Oct. 19, 1956 (0.062-in. wire in place)
3. Newton, Gould and Kaiser, Analytical Design of Linear Feedback Systems, John Wiley & Sons, Inc., New York 1957, p 325
4. See Appendix
5. Chestnut and Mayer, Servomechanisms and Regulating System Design, John Wiley & Sons, New York 1951, p 274

APPENDIX

Controller Transfer Function

With the reset rate set on 1 minute per repeat, the corner frequencies are 1 and $\frac{1}{200}$ or .005 radians/min. The respective time constants are 1 and 200 min. With a controller gain of 100 and a reset gain of 200,

$$H_1 = \frac{(100)(200)(s + 1)}{(200s + 1)}$$

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