

ABSTRACT

The frequency response of a pilot scale laboratory distillation column, separating a binary mixture of methanol and water, was obtained using the Pulse Testing technique. The column was a ten plate, bubble cap, 9-inch glass column. The forcing was carried out separately on the flows of the reflux, the feed and the steam, and the response was the temperature of different trays. The results obtained showed that the response of a tray was controlled by the major concentration lag due to mass-transfer dynamics in the liquid over the tray and by smaller hydraulic lags from the point where the forcing pulse was introduced. The major time constant for the trays above the feed was nearly same for each tray and did not differ much with the forcing on steam or the reflux. This was attributed to two factors; the same value of vapor-liquid equilibrium constant and nearly constant liquid flow rate in this section of the column. No frequency response information could be obtained for the trays above the feed while pulse forcing the feed. The trays below the feed had lower major time constants for all forcings because of higher equilibrium constant and increased liquid flow rate. These time constants were the same for the forcings on the reflux and the feed. In case of forcing on the steam, an additional factor contributing to the temperature response of bottom trays was the change in pressure at the bottom of

the column upon the introduction of the pulse. The time constants obtained for this case were lower.

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NOMENCLATURE

A, B, C, D	Defined by equations (3.3.2) through (3.3.5).
A_n	Fourier integral coefficient, defined as per equation (3.2.3).
a_k, b_k	Fourier series coefficients, defined as per equation (3.2.1).
DAR	Dynamic Amplitude Ratio or system Gain, $^{\circ}F/gpm$ or $^{\circ}F/inch$.
DRA	Dynamic Response Angle or system Phase Lag, degrees.
$D(t)$	Lag-window function.
e	Base of natural logarithm.
$f(t)$	A function in t-domain.
$G(s)$	Transfer function in s-domain.
$G(j\omega)$	Transfer function in frequency domain.
$Im(\omega)$	Imaginary part of $G(j\omega)$.
j	$= \sqrt{-1}$
n, m	Number of intervals response and input functions (respectively) are divided.
K_1	Number of data points read over first time interval of Input pulse.
K_2	Number of data points read over second time interval of Input pulse.
K_3	Number of data points read over first time interval of Output pulse.
K_4	Number of data points read over second time interval of Output pulse.

M.R.	Ratio of magnitudes of output and input Fourier transforms, giving system Gain.
s	Domain of Laplace transform.
$S(\omega)$	Complex number giving both magnitude and phase of coefficient density for non-periodic function, defined as per equation (3.2.4).
$s(\omega)$	Frequency content, being magnitude of $S(\omega)$.
$s(\omega)_n$	Normalised frequency content.
$\text{Re}(\omega)$	Real part of $G(j\omega)$.
t	Real time, seconds.
T_x	Input pulse width, seconds.
T_y	Response pulse width, seconds.
T_0	Initial lag time for response function, seconds.
T_m	Lag time for response function at which first peak appears, seconds.
T_p	Final lag time for response function (\underline{T}_y), seconds.
$x(t)$	Input or Forcing pulse function.
$y(t)$	Output or Response pulse function.
$y^*(t)$	Lag-window corrected response function, as per equation (3.5.3)
Δt_x	Interval width on forcing function, seconds.
Δt_y	Interval width on response function, seconds.
Δt_1	First time interval size of input pulse data, seconds.
Δt_2	Second time interval size of input pulse data, seconds.
Δt_3	First time interval size of output pulse data, seconds.

- Δt_4 Second time interval size of output pulse data, seconds.
- ω Frequency, domain of Fourier transform, Rad/sec.
- ω_f Fundamental frequency of periodic function.
- $\phi(\omega)$ Phase lag angle, difference of angles of Fourier transforms of output and input pulses, defined as per equation (3.1.4).
- $\rho(\omega)$ Coefficient density, defined as per equation (3.2.4).
- $\sigma(\omega)$ Angle of complex number, $S(\omega)$.
- λ Parameter for lag-window function, defined as per equation (3.5.2).
- ξ Parameter for lag-window function, defined as per equation (3.5.1).

SUBSCRIPTS:

- n Normalised.
- o At zero frequency or steady state.
- x For input.
- y For output.

OPERATORS:

- $F()$ Fourier transform operator.
- $L()$ Laplace transform operator.

TRAY SEQUENCE:

The tray number indicated refers from the top of the column.

CHAPTER I

INTRODUCTION

The advantages of frequency response methods for the dynamic analysis of physical systems are well known and will not be described at length here. It is sufficient to say that the consideration of system response in the frequency domain provides a condensation of the dynamic behavior into a compact form which remains generally applicable regardless of the type of input, as long as the system remains linear. Ceaglske (1,2) points out general features of frequency response plots and more recently detailed application of Bode plots are given by Murill, Pike and Smith (3,4,5).

The purpose of the present investigation was to obtain the frequency response of a pilot scale laboratory distillation column using the pulse testing technique. The response was of different tray temperatures to respective forcings on steam, feed and reflux flow rates.

The merits of obtaining frequency response by pulse forcing the forcing functions will be discussed in the next chapter. Suffice to say that during pulse testing the forcing function is upset from its steady state for small finite interval of time and system time domain response to this forcing is observed. The time domain input and output of the system lead to the evaluation of the frequency response of the system.

In the control of binary distillation columns, the controls are usually based on some tray temperature of the column,

other parameters like pressure of the column, being assumed to be constant. The Bode plots obtained for a tray temperature response for each forcing on steam, feed or reflux could be used to determine the optimum settings of the controllers on steam, feed and reflux lines respectively in order to obtain optimum feedback control. However appreciable use of the plots would be postulating a model in relation to a plate temperature and particular forcing function and using such a model for the feed forward control of the column. A detailed description for such a scheme has been discussed by Lubyen (6), MacMullan et al (7), Shinsky (8) and Woolverton et al (9) and others (10,11,12,13). DeBolt and Powell (14) use direct frequency response analysis to study the basic control algorithm of a direct digital control.

The frequency response obtained, being based on the assumption of the linear behavior of the column during the pulse test, leads to the linearised Bode plots valid only over a small operating envelope. This leads to only linearised models for a non-linear system like a distillation column and thus it is necessary to affect feed forward control in the small envelope of the operating conditions, within which postulated models are obtained.

CHAPTER II

DYNAMIC TESTING METHODS AND

REVIEW OF THE LITERATURE

Before discussing in detail the pulse testing method, a brief statement of the different types of dynamic testing is presented.

THEORETICAL CONSIDERATIONS:

Quite often the dynamic behavior of the process can be closely determined by a theoretical approach. Models of the process can be assumed for which the equations are obtained through the application of appropriate mass, energy and momentum balances. The mathematical models may then be used profitably either in the design of processes, their control systems or both simultaneously. Such an approach for a distillation column has been presented by many workers, notably by Armstrong and Wood (15,16,17). To minimise the complexity of the model, the approach however requires the postulation of many assumptions.

SINUSOIDAL TESTING:

The classic route to a description of the dynamics of a linear system is by impressing a sine wave of various frequencies on the input to obtain the frequency response of the output function. The method is still used for simpler systems. The method and data reduction techniques are available in

numerous standard references such as that by Caldwell, Coon and Zoss (18).

STEP FUNCTION TESTING:

The method is to force a step change in the input and obtain an output. One way of data reduction is by a graphical technique, that can be used when the system can be approximated by a linear system and can be described by first order differential equation (18,19). The second method is more generally useful with the only requirement being that the system must be approximately linear. The method involves a Fourier series solution of the transient wave (20,21,22). Several papers deal with the dynamic analysis of distillation columns from the transient behavior of the column (23,24,25,26).

PULSE AND IMPULSE TESTING:

Pulse testing methods were developed by M.I.T. for determining the dynamic response of complex control systems such as those found in aircraft. The data reduction to frequency response involved a Fourier series method which has been described by several authors (27,28,29,30,31,32,33). The application of the pulse testing method has been in progress for several years. A review of this work has been discussed by Hougen (28). The treatment of pulse test data to yield frequency response has been discussed in detail by Clements and Schnelle (31). The impulse response method has not been profitably used by the chemical industry and has been of theoretical interest only. A detailed status of pulse testing

method is presented later in the chapter.

RANDOM SIGNAL TESTING:

The use of random signals in the dynamic response testing of process systems is now becoming more common. The method has the advantage of not upsetting the plant systems, as the plant records themselves will contain sufficient random noise to permit cross-correlation (34,35). Many problems must be solved, however, before the method of random signal can be used in the routine determination of the dynamics of the process (12,34).

PULSE TESTING METHOD

The need for dynamic testing of chemical systems using the pulse testing technique has been stressed by many workers, particularly Hougen (28).

In conducting a pulse test, an input variable is changed in a pulse-like manner. This means that the variable is displaced from its equilibrium position for only a finite time. Before and after the duration of the pulse, this variable is held constant. The outputs of a stable system, whatever they may be or however many there may be, will also behave in a pulse-like manner, although some of them may exhibit oscillations before returning to their initial steady state.

In a pulse test the principal requirements are that the system be driven sufficiently hard, so that the dynamics of the system are excited but not so hard that the capacity of the system to respond is exceeded. From one and only one,

properly conducted pulse test, the frequency response characteristics of the system can be obtained. Thus instead of conducting the tests by direct methods at several discrete frequencies, only one test disturbance is used. In a sense, the single pulse is designed to excite the system with all the frequencies at once. Then by appropriate computational techniques the frequency response information is extracted therefrom. Another advantage of the pulse test over the classical sinusoidal test or step test is that the system returns to original conditions after a small finite interval of time, so that product quality and rate are not much affected.

Aseltine (36) has discussed the Fourier transform reduction of pulse test data to the frequency domain. Clements, Jr., (30) has discussed in detail the method of pulse testing and applied it to obtain extraction column dynamics. Earlier notable use of pulse testing was by Head, Hougen and Walsh (27,29,37,38). Driefke et al (39) exhaustively studied pulse testing in relation to the existence of an optimum pulse.

Banham, Jr., (40) used the pulse testing technique to obtain dynamics of a steam generating system. A wide use of the pulse testing method has been used to obtain dynamics of the simpler systems like heat exchangers. Renfro, Jr., (32) used pulse testing to obtain multicomponent bubble cap distillation column dynamics, followed by similar investigations by Fogle, Jr., (33) on a sieve plate column. The pulse was forced on the

feed composition and the response pulse was tray liquid composition. However not until recently was the tray temperature response of a distillation column considered. Powell and DeBolt (41) obtained such frequency response characteristics for a distillation column, separating a binary solution, by pulse forcing the reboiler steam. More recently Marino, Perna and Stutzman (42,43) obtained frequency response of tray temperature of a distillation column, separating a binary solution, by pulse forcing the reflux flow rate.

Being easy to measure with least time lag, the tray temperature is a convenient control variable, particularly for a distillation column, separating a binary solution. Thus it is advantageous to measure dynamics of such a distillation column, based on the tray temperature response.

CHAPTER III

MATHEMATICAL BACKGROUND

The transfer function, $G(s)$, of a single-input, single-output linear system may be defined as the ratio of the Laplace transform of the system output and input. Symbolically using the definition of the Laplace transform,

$$G(s) = \frac{L\{y(t)\}}{L\{x(t)\}} = \frac{\int_0^{\infty} y(t) e^{-st} dt}{\int_0^{\infty} x(t) e^{-st} dt} \dots\dots\dots (3.1.1)$$

where s is the complex variable of the Laplace transform.

It can be shown (36,44) that the frequency response of the system may be derived analytically from the transfer function by substituting $j\omega$ for s . Expressing the resulting complex number in polar form gives the result,

$$G(j\omega) = \frac{\int_0^{\infty} y(t) e^{-j\omega t} dt}{\int_0^{\infty} x(t) e^{-j\omega t} dt} = \{ \text{M.R.}(\omega) \} e^{-j\phi(\omega)} \dots\dots\dots (3.1.2)$$

That is, the magnitude of a complex number is the magnitude ratio and its angle is the phase angle of the system frequency response. With output and input being zero from $-\infty$ to 0, we note that $G(j\omega)$ as expressed in equation (3.1.2) is the ratio of the Fourier transform of the output and input. By making use of the properties of complex numbers, equation (3.1.2) can be expressed as,

$$\text{M.R.}(\omega) = \frac{| F\{ y(t) \} |}{| F\{ x(t) \} |} \dots\dots\dots (3.1.3)$$

and

$$\phi(\omega) = -\left[\text{angle}\{F\{y(t)\}\} - \text{angle}\{F\{x(t)\}\} \right] \dots\dots\dots (3.1.4)$$

where $F()$ indicates the Fourier transformation operator. If the Fourier transform integrals of equation (3.1.2) are evaluated numerically, we can obtain frequency response of the system with the use of equations (3.1.3) and (3.1.4).

Consider the forcing function, $x(t)$, as a closed pulse, i.e., it is zero at $t = 0$, assumes a finite value for a finite time interval T_x and then is again zero for $t > T_x$.

Let us make an assumption, which is valid for most of the systems, that the resulting response, $y(t)$, to pulse input is also a pulse of same type, i.e., it has a finite value only for a finite interval of time $0 < t < T_y$, after which $y(t)$ approaches to its steady state value so closely that any difference can no longer be distinguished.

Then equation (3.1.2) becomes,

$$G(j\omega) = \frac{\int_0^{T_y} y(t) e^{-j\omega t} dt}{\int_0^{T_x} x(t) e^{-j\omega t} dt} \dots\dots (3.1.5)$$

FREQUENCY CONTENT OF PULSE FUNCTION:

In order to conceive the physical mechanism of pulse testing method, we consider the derivation of equation (3.1.5) by consideration of the Fourier integral. This leads to the concept of the frequency content of a non-recurrent pulse. Instead of forcing the system to a large number of discrete frequencies, applied one at a time, we apply one input pulse of arbitrary shape and we find that the frequency response for a continuous band over a large range of frequencies is derivable from this pulse response.

Consider a periodic function, $f(t)$, of period T . With the Fourier series expansion, it can be expressed as a summation of individual trigonometric components, each possessing definite frequency and magnitude. Thus $f(t)$ can be expressed as the series,

$$f(t) = \sum_{k=0}^{\infty} \{ a_k \sin(k\omega t/T) + b_k \cos(k\omega t/T) \} \dots (3.2.1)$$

where $\sqrt{a_k^2 + b_k^2}$ represents total amplitude of the component of angular frequency $k\omega/T$. In complex exponential form,

equation (3.2.1) can be expressed as

$$f(t) = \sum_{\eta=-\infty}^{\infty} A_{\eta} e^{j t \eta \omega_f} \dots\dots\dots (3.2.2)$$

where

$$A_{\eta} = \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} f(t) e^{-j t \eta \omega_f} dt \dots\dots\dots (3.2.3)$$

By inspection of equation (3.2.3), we find that A_{η} approaches zero as T becomes infinitely large — for the case of a non-periodic function like non-recurrent pulse. To avoid this difficulty, the equation (3.2.3) is modified to define the coefficient density,

$$\rho(\omega) = T A_{\eta} = \int_{-\frac{T}{2}}^{\frac{T}{2}} f(t) e^{-j \eta \omega_f t} dt \dots (3.2.4)$$

and to regard $\rho(\omega)$ as defining the frequency content of a function. For a periodic function, $\rho(\omega)$ exists only at discrete frequencies that are integral multiples of the fundamental frequency ($\omega_f = 2\pi/T$), corresponding to discrete terms in Fourier series expansion.

For the case of total non-periodic pulse, $T \rightarrow \infty$, the fundamental frequency, ω_f , becomes infinitesimal, and equation (3.2.4) can be written as

$$S(\omega) = \lim_{T \rightarrow \infty} \rho(\omega)$$

$$= \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt \quad \dots\dots\dots (3.2.5)$$

which is the Fourier transform of $f(t)$.

Being a complex number, $S(\omega)$ expressed in polar form possesses both a magnitude, $s(\omega)$, and an angle, $\sigma(\omega)$.

$$S(\omega) = s(\omega) e^{j\sigma(\omega)} \quad \dots\dots\dots (3.2.6)$$

Since the frequency content of non-periodic pulse is a continuous function of frequency and thus contains a continuous frequency spectrum, if such a pulse is applied as input to a physical system the output will consist of the combined response of these frequencies. The magnitude of the forcing at a particular frequency depends on the relative frequency content and it is possible to have zero values at certain discrete frequencies. Remembering the definition of frequency response, then from equation (3.2.5) and the properties of complex numbers one can write magnitude ratio as the ratio of frequency content of the output pulse, $y(t)$, to that of the input pulse, $x(t)$.

$$\text{M.R.} = \frac{|s(\omega)_y|}{|s(\omega)_x|} = \frac{|F(y(t))|}{|F(x(t))|} \quad \dots\dots (3.2.7)$$

and the phase angle as

$$\phi = -\{\sigma_y - \sigma_x\} \quad \dots\dots (3.2.8)$$

The expression for $s(\omega)$ can be easily derived, using

equation (3.2.5) for many mathematically simple pulse shapes. For the purpose of comparing different shapes with regard to frequency content, it is common practice to plot the normalised frequency content, $s(\omega)_n$, rather than $s(\omega)$ itself.

$s(\omega)_n$ is given by,

$$s(\omega)_n = \frac{s(\omega)}{s(0)} \quad \dots\dots (3.2.9)$$

Thus the normalised frequency content for all shapes start at 1.0 at $\omega = 0$. Behavior of frequency content depends on both pulse shape and pulse width, T_x . If the normalised frequency content is plotted against ωT_x , the plot depends on pulse shape only. In figure 1 plots for frequency content of some simple pulse shapes are given.

The close relationship between the frequency content, especially of the input pulse and the frequency response derived from a pulse test is of paramount importance to the efficient recovery of frequency response data from the pulse test. Theoretically with the pulse test one can obtain frequency response over all the frequencies except where $s(\omega)_n$ is zero, but practical limitations, like the accuracy of the numerical evaluation of the Fourier transforms, data reading errors etc. limit valuable results to the values of $s(\omega)_n$ going down to 0.3 before first zero occurs.

NUMERICAL EVALUATION OF THE PULSE:

In equation (3.1.5) applying the identity,

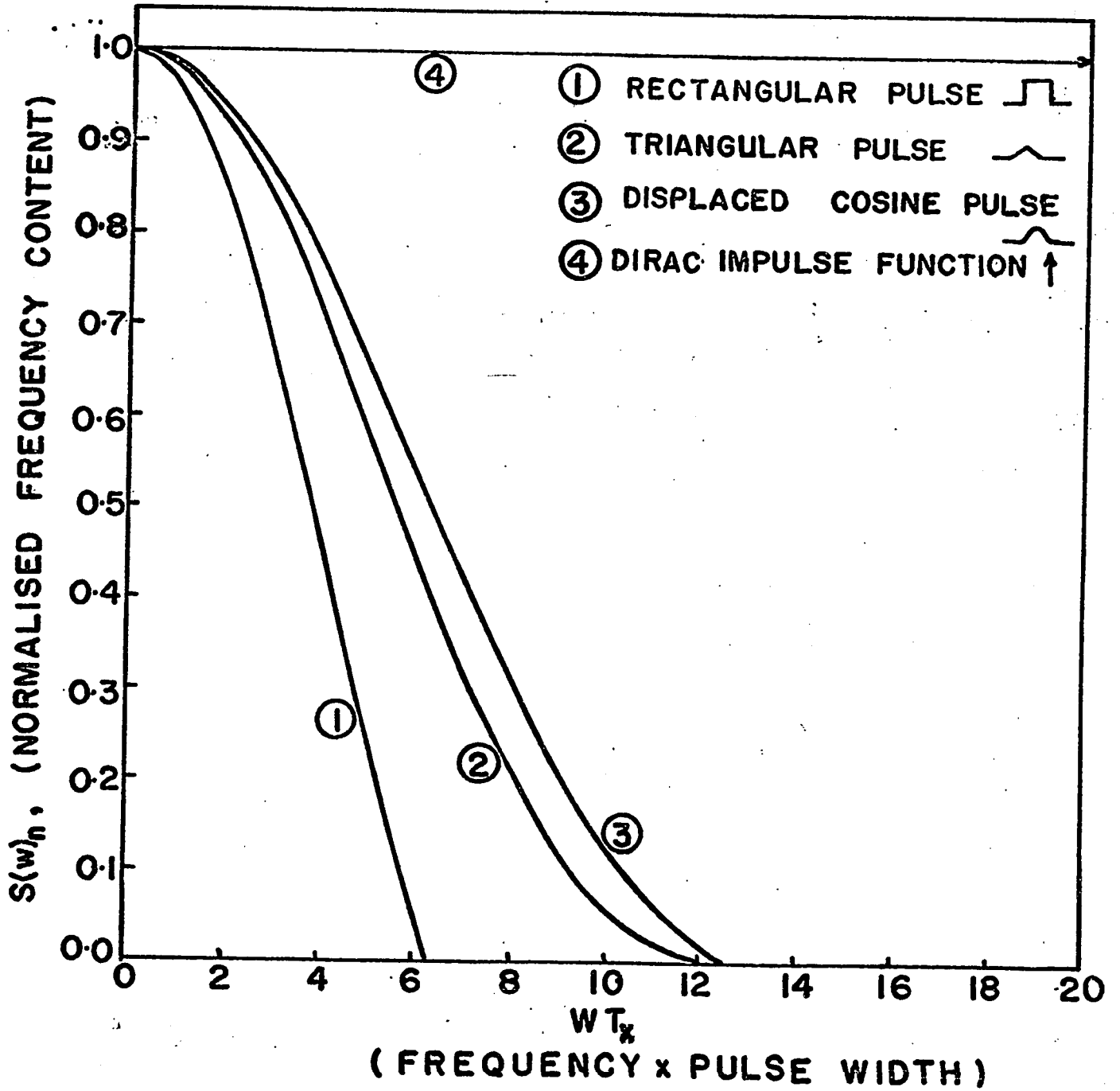


Figure 1. Normalised Frequency content of some mathematically expressible Pulses.

$$e^{-j\omega t} = \cos \omega t - j \sin \omega t$$

to both integrals, gives

$$G(j\omega) = \frac{\int_0^{T_y} y(t) \{ \cos \omega t - j \sin \omega t \} dt}{\int_0^{T_x} x(t) \{ \cos \omega t - j \sin \omega t \} dt} \quad \dots (3.3.1)$$

The algebraic reduction of the above equations gives the basic equations used for obtaining frequency response data from pulse tests.

Denoting

$$A = \int_0^{T_y} y(t) \cos \omega t dt \quad \dots (3.3.2)$$

$$B = \int_0^{T_y} y(t) \sin \omega t dt \quad \dots (3.3.3)$$

$$C = \int_0^{T_x} x(t) \cos \omega t dt \quad \dots (3.3.4)$$

and
$$D = \int_0^{T_x} x(t) \sin \omega t dt \quad \dots (3.3.5)$$

$$M.R. (\omega) = \sqrt{Re^2(\omega) + Im^2(\omega)} \quad \dots (3.3.6)$$

$$\phi(\omega) = \tan^{-1} \left[\frac{Im(\omega)}{Re(\omega)} \right] \quad \dots (3.3.7)$$

$$s(\omega)_n = \frac{\sqrt{C^2 + D^2}}{\int_0^{T_x} x(t) dt} \quad \dots (3.3.8)$$

where

$$Re(\omega) = \frac{AC + BD}{C^2 + D^2} \quad \dots (3.3.9)$$

$$\text{Im}(\omega) = \frac{BC - AD}{C^2 + D^2} \quad \dots\dots (3.3.10)$$

Thus the computational problem is the evaluation of A, B, C, D from experimental data. The most direct method is the application of a quadrature formula such as trapezoidal rule. The method, with some modification, is used to compute A, B, C and D. The modified method is listed in appendix C.

PROGRAMMING THE CALCULATIONS:

To facilitate the computations required by equations (3.3.2) through (3.3.10), the author has written a program for the IBM-360/65 computer using the modified trapezoidal rule, assuming the input and output pulses for a particular test are broken up according to the scheme shown in the figure 2.

As illustrated in the figure, the first portion of the curve changes more rapidly than the latter portion. It was necessary to use smaller time intervals in the first portion in order to have straight line segments. However to avoid the inconvenience of too much curve reading larger time intervals were used in the second portion. The program was written to accept two different increments of time in both the input and output pulses. Thus the program input included the input data points x_0 through x_m , the output data points y_0 through y_n , the four Δt (interval size) values, two each for $x(t)$ and $y(t)$, and the number of points read using each Δt . These quantities are indicated in the figure 2.

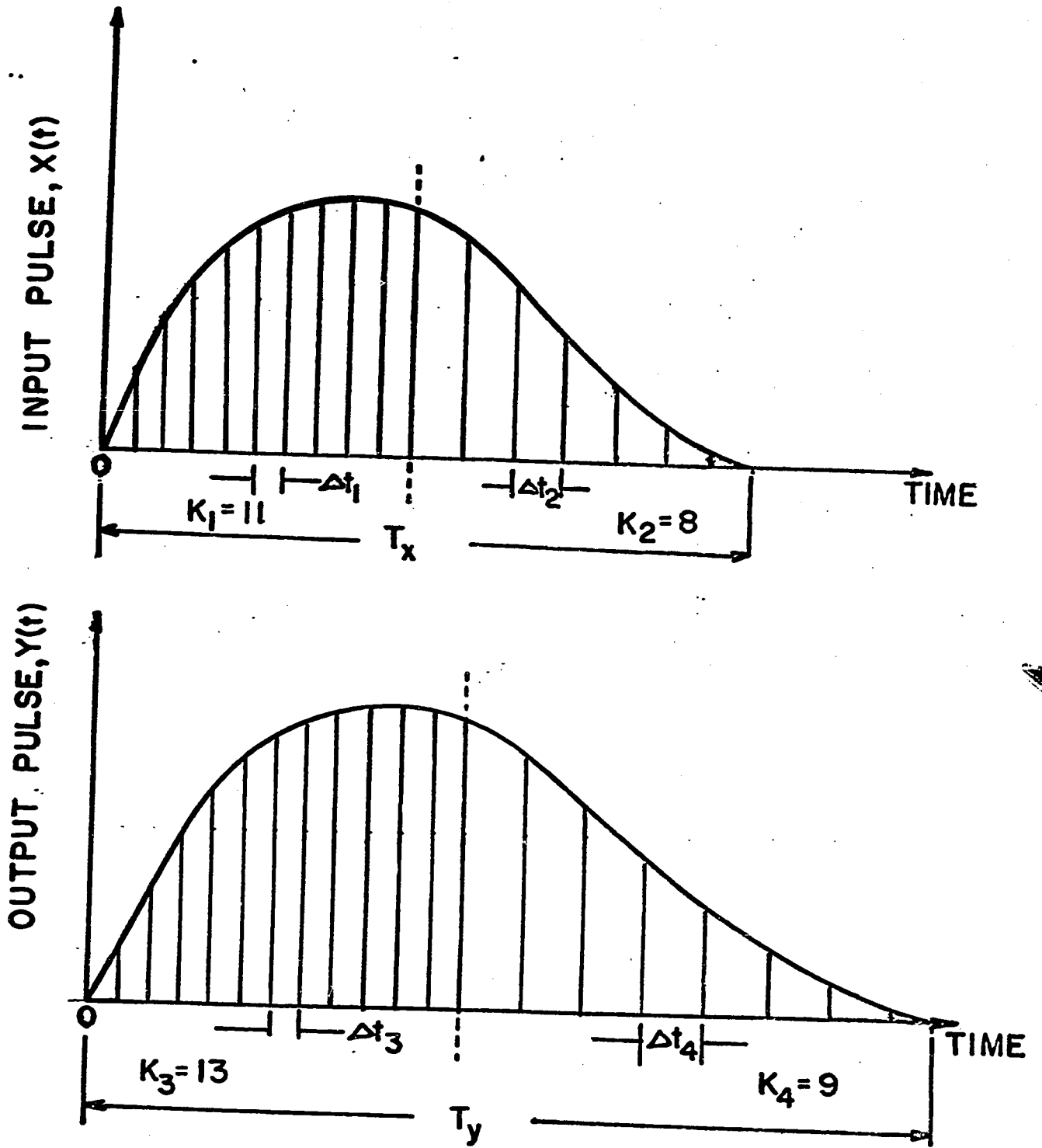


Figure 2. Scheme for dissection of typical Input and Output Pulses.

By means of the program the area under the product curves is numerically calculated as specified by equations (3.3.2) through (3.3.5). These areas are calculated separately for each Δt portion and summed to yield the total values of A, B, C and D. Magnitude ratios and phase angles are then computed using equations (3.3.6) and (3.3.7), beginning at a specified value of ω , incrementing it by a specified value of each additional frequency, until the desired maximum is reached. Also simultaneously for each value of ω , $s(\omega)_n$ is calculated and printed out.

The program was modified to calculate also the magnitude and the phase angle of the Fourier transform of the input and output pulses separately and from the plots of these quantities, magnitude ratio or Dynamic Amplitude Ratio (DAR) and phase lag or Dynamic Response Angle (DRA) were calculated. Explanation for this modification is given in Chapter V.

A detailed description of the computer program is given in appendix C.

LAG-WINDOW:

The technique of correlation functions to analyse the noise in the system response has been proposed (45). Based on it the response function is operated upon by a function to yield a response containing little or no noise component. Various workers have proposed different models (35,45,46,47,48).

Wallaston and Swanson (46) have analysed the character-

istics of the response function of chemical processes. In a typical plant dynamic test, because of process disturbance, the output, both steady state and transient values, most certainly contain noise. Their investigation of the lag-window concept, lead them to a simple mathematical expression which could be considered to filter the noise component of the response function. However their investigation was based on first and second order simulated chemical processes.

The two-parameter lag-window function, $D(t)$, presented by them for a pulse test is:

$$\begin{aligned}
 D(t) &= 1 && \text{for } T_0 \leq t \leq T_p - \lambda(T_p - T_0) \\
 &= \left[1 - \left(\frac{t + \lambda(T_p - T_0) - T_p}{\lambda(T_p - T_0)} \right)^2 \right]^\xi && \text{for } T_p - \lambda(T_p - T_0) \leq t \leq T_p
 \end{aligned}$$

..... (3.5.1)

where

- T_0 Initial lag time for response function.
- T_p Final lag time for response function.
- t Time.

and λ and ξ are the two parameters. Wallaston and Swanson note that this lag-window is specially effective for output curves which are one sided as in the case of response curves of most of the processes. Their extensive studies, based on simulated chemical processes, yield the best choice of λ to be,

$$\lambda = \frac{T_p - T_m}{T_p - T_o} \dots\dots\dots (3.5.2)$$

where T_m is the time lag at which the first peak occurs in the response curve. The choice of 1 or 2 for ξ makes a more effective lag-window when the variance of the output curve is high. Normally a value of $\xi = 1$ should be used, since for reasonable accurate results larger values of ξ cause too much distortion.

With this choice of parameters and computing of $D(t)$, the corrected response function,

$$y^*(t) = D(t) y(t) \dots\dots\dots (3.5.3)$$

is considered as the true response to the input function.

In the present investigation, because of lack of further literature on use of the above simple model, the lag-window concept was used for the response obtained to forcings on steam only. A subroutine to main computer program was added to compute $D(t)$. The subroutine is listed in appendix C.

CHAPTER IV

EXPERIMENTAL

The plan of the experimental investigation was preceded by a specific review of the literature, cited earlier, for pulse testing methods, including operational considerations to obtain distillation column dynamics. The existing distillation unit was operated to study its bottlenecks while pulse testing the column and needed modifications were done on the unit as well as applied to pulse testing method.

In this chapter we discuss materials and apparatus used, preliminary experimental runs (including main modifications ^{made} done) and main experimental runs, including the step and the sinusoidal tests performed on the column. The step and the sinusoidal tests were performed to test check the results obtained with the pulse test.

MATERIALS AND APPARATUS

The apparatus used in the investigation was a pilot scale laboratory distillation column. The methanol-water system was used in the binary distillation. The methanol was the grade A-412 Fisher certified A.C.S. from Fisher Scientific Company. The services included cooling water, steam, electricity and instrument air. A schematic diagram of the equipment is shown in the figure 3.

The column was constructed of Q.V.F., 9-inch glass pipe

NOTATION FOR FIGURE 3.

- A Overhead Condensate Drum.
- B Overhead Condenser.
- C Reflux Pump.
- D Bottoms Cooler.
- F Feed Preheater.
- G Reflux Distribution Plate.
- H Feed Distribution Plate.
- J Product Control Valve.
- K Transfer Pump.
- L Feed Pump.
- M Reflux Control Valve.
- N Feed Control Valve.
- P Bottoms Control Valve.
- R Reboiler.
- S Steam Control Valve.
- T Transducer, mV to psi.

with inside diameter of 8.38 inches and outside diameter of 9.25 inches. The column contained ten brass trays, each tray with two 2-inch copper bubble-caps. The bubble cap risers were $1\frac{7}{8}$ inches in diameter and the circular downcomers were 2-inch copper pipes. The downcomer pipe extended $1\frac{1}{2}$ inches over the tray, providing the necessary weir height. Besides the column contained two distribution plates, one each for the reflux and the feed. The tray spacing, including distribution plates, was one foot.

The temperature of each tray, including distribution plates, was measured with copper-constantan thermocouples, installed in thermowells drilled into the tray metal.

The overhead system consisted of a total condenser integrated with a small overhead reflux drum, and a product tank. The condenser was two shell and tube copper exchangers operated in series. Each exchanger contained ten $\frac{1}{2}$ inch OD X 4 feet long copper tubes placed in a 3-inch shell. Cooling water to condenser was manipulated with a manual valve and rotameter. An attempt was made to keep the condensate temperature constant with a separate control system. Part of the overhead condensate was withdrawn as overhead product under liquid level control system to the product tank. The tank was horizontal 18 inch diameter X 28 inch long stainless steel tank.

The bottom system consisted of a thermosyphon reboiler, bottoms cooler and bottoms tank. The reboiler was a 8 in. dia.

shell and tube (48-5/8 in. OD X 18 in. long) copper heat exchanger mounted on the bottom of the column. Steam was used as the heating medium, with the steam rate controlled by the tray 7 (from the top) temperature control system.

The bottoms were withdrawn using a bottoms liquid level control system and cooled through a bottoms cooler before storage in the bottoms tank. The bottoms cooler consisted of two shell and tube exchangers in series and similar to the overhead condenser. Cooling water to it was also manually controlled. The bottoms tank was a horizontal 24 in. dia. X 48 in. long stainless steel tank.

The reflux was under flow control. Part of the overhead condensate was pumped through the reflux flow control valve onto the reflux distribution plate.

Two vertical stainless steel tanks (24 in. dia. X 36 in. high) were used as feed tanks. Material from the product tank and the bottoms tank was batchwise transferred with the transfer pump. Blended feed was pumped through the feed preheater and onto the feed distribution plate, located over the tray 7. Steam to the preheater was controlled manually, with a pressure reducer, to keep the feed preheater (outlet) temperature constant.

A list of auxiliaries including pumps, control valves, rotameters and other instruments used in the operation and pulse testing of the column is given below.

PUMPS:

Two Cole-Parmer nylon head centrifugal pumps were used as the feed and the transfer pump.

Feed Pump: Model 7114 (10.5 psig max.head), with capacity of 750 gph at one foot(water) head. This pump was also used as a transfer pump.

Transfer Pump: Model 711(9.8 psig max.head), with capacity of 650 gph at one foot(water) head.

Reflux Pump: ordinary cast iron body, gland packed, centrifugal pump coupled with 110 V, 1140 RPM, $\frac{1}{6}$ HP motor was used, as the Cole-Parmer pumps developed a seal leak while operating on pure methanol.

ROTAMETERS:

Four, Brooks Full-View rotameters were used for the following service.

Reflux Flow Rate: Type 6-1110-5500-A E, indicating max. flow of 0.5 usgpm(sp.gr. 0.73). The float was connected with a system which transduced float lift into a pneumatic signal.

Feed Flow Rate: Type 7-1110-5500A, indicating max. flow of 0.8 usgpm(sp.gr. 0.98). The float was connected with a system which transduced float lift into pneumatic signal.

Bottoms Flow Rate: Type 8-1110, indicating max. flow of 0.75 usgpm(sp.gr. 0.98).

Product Flow Rate: Type 6-1110, indicating max. flow of 0.14 usgpm(sp.gr. 0.73).

LEVEL TRANSMITTERS:

Foxboro Differential Pressure (D/P) Cell: Type 15A-LS2, with output range of 3-15 psig at 10 inch water gage setting, to transmit the bottom level of the column.

Honeywell Direct Action Diaphragm Type: Liquid level transmitter, with output range of 3-15 psig at 10 inch water gage setting, to transmit overhead condenser reflux drum level. The diaphragm was of 316 S.S.

CONTROLLERS/RECEIVERS:

Five Foxboro Consotrol units, consisting of model 52A controller coupled with model 53 receiver for indicating and controlling of feed flow rate, reflux flow rate, reflux drum level, bottom level of the column and one tray (tray 7) temperature of the column.

CONTROL VALVES:

Five model 1403, Honeywell control valves were used for the following service in the experimental set up. All valves had specification of $\frac{1}{2}$ -inch body size, 9/16 inch lift, linear contour, non-lubricated, teflon packed, 316 S.S.trim, C.I.body.

Reflux Control Valve: with cv of 0.63

Feed Control Valve: with cv of 0.63

Bottoms Level Control Valve: with cv of 1.6

Reflux Drum Level Control Valve: with cv of 0.36

Steam Control Valve: with cv of 4.0

THERMOCOUPLE REFERENCE JUNCTIONS:

Acromag Model 335: A 25-channel, with 0°C reference for type T (copper-constantan) thermocouple reference junction, operating for all thermocouples (one at a time) connected to a Honeywell Multipoint temperature recorder.

Acromag Model 325: A single channel, with 0°C reference for type T (copper-constantan) thermocouple reference junction, used for particular tray temperature recording with Dynograph recorder.

TEMPERATURE RECORDER:

Honeywell Type 153 Elektronik Multipoint Recorder:

A 16-point, connected up with model 335 Acromag reference junction to record all temperatures. Input range is 0.5 to 5.5 mV.

TRANSDUCERS:

Swartout Autoronic Power Relay (model No. P2R/19): with 1-5 ma input and 3-15 psig output (supply air at 20 psig) for transducing output from Function Generator to pneumatic signals.

Statham General-Purpose Strain Gage Pressure Transducer (model PG 769): used to transduce pneumatic signals (3-15 psig) of feed and reflux flow rates into electric

signals.

Sanborn Differential Transformer (model 585-DT-500 Linearsyn): used to transduce linear stem motion of the steam control valve into electric signals. Specified factor for the transducer was 96mv of output per inch of valve-stem travel.

Foxboro EMF/Pneumatic Transmitter: consisting of model 40E control relay (reference at 25°C) coupled with type 33EMF/Pneumatic converter to transduce tray 7 (from the top) temperature into a pneumatic signal which was fed to the temperature control controller/receiver.

FUNCTION GENERATOR:

Hewlett-Packard Model 3300A Function Generator: used for the generation of sinusoidal, square and triangular waves with a frequency range of 0.01cps to 100 KC in seven decades.

Hewlett-Packard Model 3302A Trigger Phase Lock Plug-in: used in the present investigation to provide a single cycle or a continuous cycle function with characteristics controlled with the model 3300A.

Hewlett-Packard Model 3301A Auxiliary Plug-in: used in place of model 3302A when continuous cycles of frequencies down to 0.0001 cps was required. This was needed for sinusoidal testing of the column at low frequencies.

HIGH SENSITIVITY RECORDER:

Beckman Type RS Dynograph Direct writing dual channel (thermal writing) recorder for recording of input pulse and response temperatures of the column. The system was composed of the following units mounted on a panel.

Dual channel Recorder (Type 508): multispeed, thermal writing, rectilinear recording.

Recorder Control Panel (Type A 560) Power Amplifier (type 462); which included a power amplifier and other operator controls (individual for each channel) with a special arrangement for rolling off frequencies above 20 cps.

Preamplifiers (Type 461B): which in conjunction with multiplier settings of Power Amplifier increased recording sensitivity to 0.01 mV/cm.

Input Couplers: The signal to the recorder was fed to the proper coupler, depending on the type of the signal. The following four couplers were used.

- (i) Type 9801 Straight-Through coupler, A-C/D-C, used for recording the output from the Function Generator.
- (ii) Type 9803 Strain-Gage Coupler, used for recording the strain-gage transducer output for measuring reflux or feed flow rate.
- (iii) Type 9805 Differential Transformer Coupler, used for recording the Differential transformer output to measure steam control valve stem displacement.
- (iv) Type 9806-A, A-C/D-C Input Coupler for recording

thermocouple output to measure the column tray temperatures. This unit was modified in order to cut off noise, due to 60 cycle pick-up, at high sensitivity (discussed later in this chapter).

All these input couplers in conjunction with other recording elements had a specified sensitivity 1 $\mu\text{V}/\text{mm}$ maximum, frequency response down 3 db at 50 cps (excluding Type 9806A), zero suppression in excess of 50 cm (chart) and drift less than 1 $\mu\text{V}/\text{hour}$.

The function diagram for introduction and measurement of input pulse and measurement of response temperatures is indicated in figure 4.

PRELIMINARY EXPERIMENTAL

In order to investigate a restricted envelope of operating conditions of the distillation column, a series of steady state runs was conducted. This envelope of operating conditions was then used in the dynamic tests. The normal feed composition was 12 wt. percent of methanol, with a tolerance of ± 0.5 percent. One modification included during the initial phase of preliminary tests was the addition of a feed preheater.

During the preliminary runs all rotameters were calibrated against the dry calibrated feed tank and were found to be within ± 1 percent of the rated values in the zone of operation.

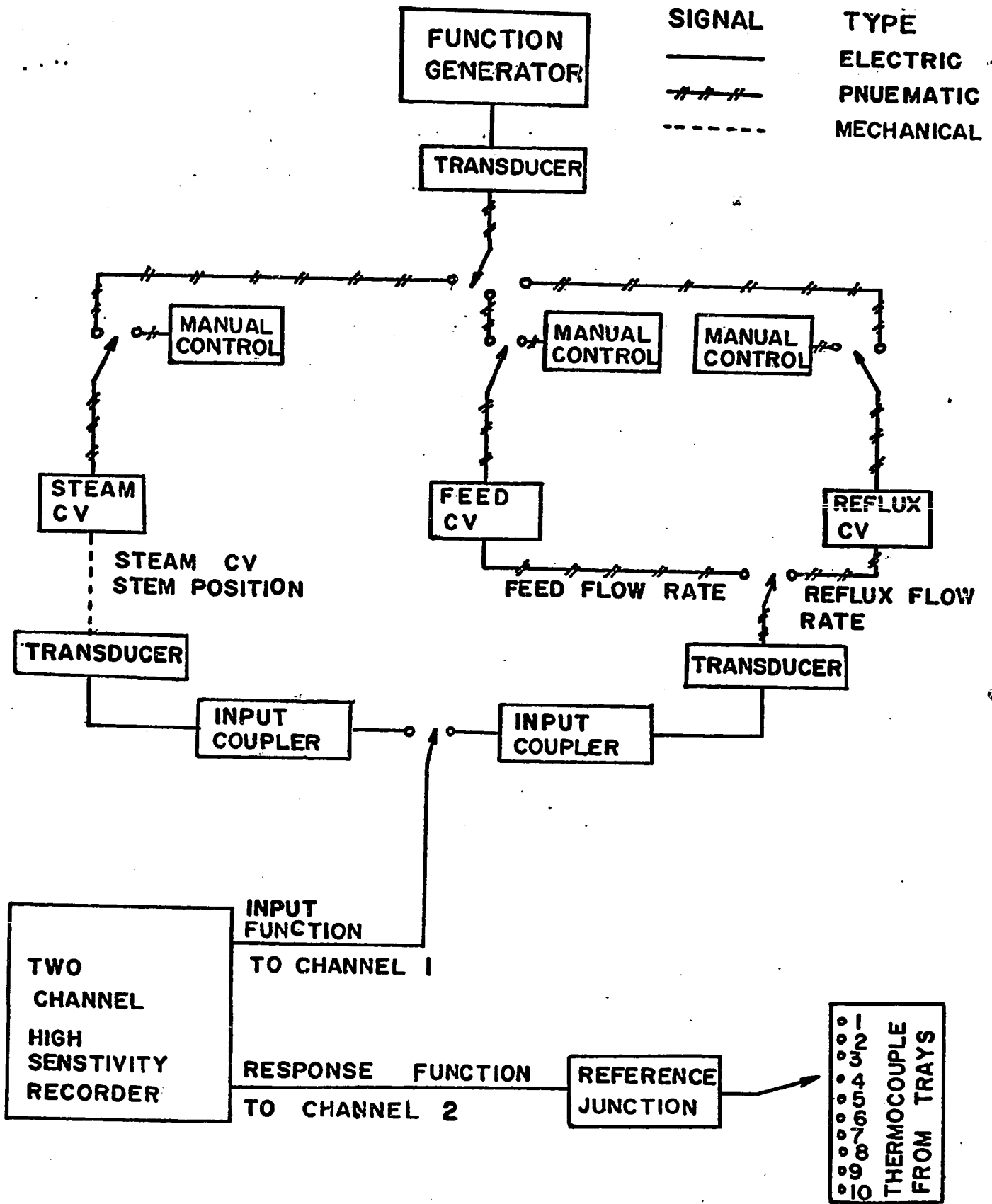


Figure 4. Functional Block diagram for Pulse Testing scheme.

The multipoint temperature recorder was calibrated with a potentiometer. The average temperature profile obtained during a steady state test is presented in figure 5 and is tabulated in appendix A. It was found that the above temperatures of the tray corresponded to the temperature of the vapor rising to the particular tray rather than the temperature of the liquid over the tray. This was due to the fact that thermowells were installed in the tray metal.

A material balance test was conducted at the steady state conditions of the column and the same is presented in appendix A.

The preliminary pulse forcing for steam, feed and reflux was carried out directly on air-signal to the particular control valve, but the forcing had to be modified because of the following reasons.

- (i) Both the feed and the reflux control valves did not have, contrary to the rating, linear contour, i.e., linear relationship between air-signal to the valve and the flow rate. No direct check for this could be effected on the steam control on the line.
- (ii) Both the feed and the reflux control valves were not reproducible in terms of air-signal vs flow rate.
- (iii) When a closed pulse disturbance was imposed on the air-signal to the reflux control valve, the resulting flow response did not close. This was due to mechanical friction in the valve.

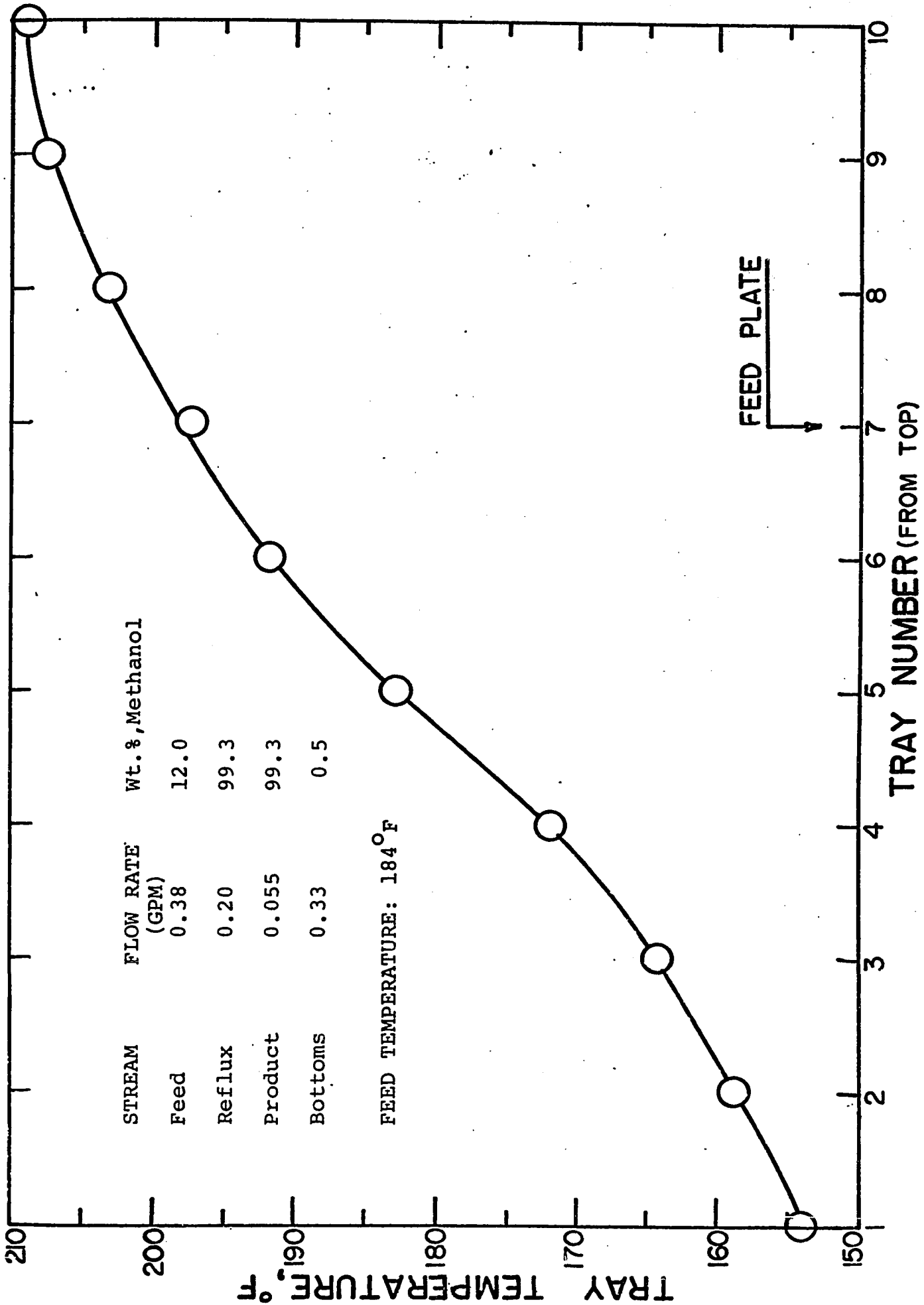
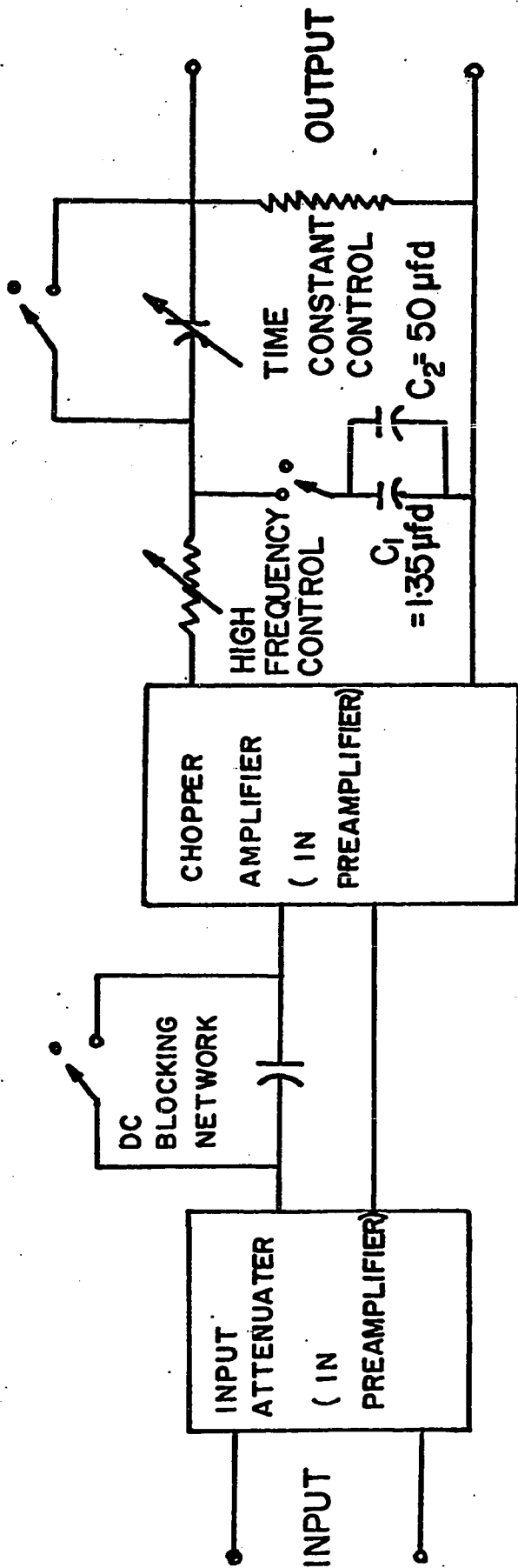


Figure 5. Steady State Temperature Profile of the Column.

(iv) The steam control valve stem position did some times drift for constant air signal to the valve, particularly right after the completion of a pulse on air signal to the valve.

With these limitations due to peculiar action of the control valves, forcing functions were based on flow rates for feed and reflux and on valve stem position in case of steam. Consequently only random shaped pulses could be introduced as other pulse shapes (triangular, sine, square), generated with the function generator, could be used only when the forcing function was on air signal to the control valve. Feed and reflux flow signals were transduced to electric signals and recorded with the Dynograph recorder. Similarly valve stem position of the steam control valve was transduced to the electric signal and recorded with the Dynograph recorder.

The recording of temperatures of different trays with the Dynograph recorder at high sensitivity included 60 cps noise of ± 0.002 mV amplitude. The noise was picked up from 110 V-60 cps electric mains in the vicinity. This noise was quite undesirable, particularly when response temperature recorded had a peak of only 0.01 mV. To cut off noise, the frequency response characteristics of the input coupler (Type 9806-A) were studied (49,50) and a 50 μ fd capacitor was placed in parallel with the existing 1.35 μ fd capacitor. The main outline of the internal system of the coupler with the preamplifier is shown in the figure 6 and the modification



SPECIFIED NOMINAL CORNER FREQUENCIES

High Freq. Switch Position	Approx. Upper Cut-off Frequencies (-3 db)
1	beyond 150 cps
2	32 cps
3	22 cps

Additional Capacitor C_2 (= 50 μ fd) was put in Parallel with original Capacitor C_1 (= 1.35 μ fd) to cut off 60 cps pick-up.

Figure 6. Functional Block diagram for Type 9806-A Coupler and Preamplifier.

is indicated. This arrangement made it possible to record temperatures without pick up of noise from the electric mains.

After normal start-up of the column, it was several hours before the column reached the steady-state. During and before reaching the steady-state all inputs were particularly kept steady and on manual control. The pulse was introduced only when the tray temperature, measured with the high sensitivity recorder, indicated no fluctuation. To avoid fluctuations in steam pressure, particularly due to a small consumption by other users, steam pressure in the main line was kept high, around 60 psig, before throttling it to the steam control valve. Because of availability of only a two-channel recorder, only the response of one tray could be recorded for a particular test. A large number of preliminary tests were conducted to investigate the optimum pulse height and width for a reasonable response. Pulse width had to be restricted to extend the upper frequency limit upto which reliable frequency response could be obtained. However discretion was used with pulse height, using up to 25 percent of steady-state value. This was necessary to obtain a meaningful response. From the step tests on the column it was indicated that this value of pulse height did not excite the non-linearities of the column.

An attempt was made to keep the reflux temperature constant during the pulse test by using a control valve on the cooling water to the overhead condenser. However the control did not prove satisfactory because of the short duration of the pulse test as compared to control system

dynamics. Reflux temperature was, therefore, controlled manually up to the introduction of the pulse.

MAIN EXPERIMENTAL

PULSE TESTING:

Pulse testing was carried out using steam control valve stem position, feed flow rate and reflux flow rate as forcing functions. Before introduction of pulse the column was brought to steady state within predetermined operating envelope and maintained at this steady state for sufficient time. During a particular test only one tray temperature was recorded. As tray 5 temperature showed large variations, even though other trays were at steady state operating temperature, its response was not recorded. Tray 7 was connected with the pneumatic control system (for start up operation) and hence its temperature response was also not recorded. Before data reduction of a particular tray temperature, it was ascertained that nearly the same temperature response was obtained for the same forcing. This restriction helped to reject at first hand incorrect responses due to drifts occurring just before or during the pulse test.

In the case of forcing on the feed data-reduction was done only to recordings of temperatures of tray 6 and below as no appreciable response was obtained for the upper trays with the chosen pulse height and width.

STEP TESTING:

The steady state gain obtained with the pulse test was checked experimentally by introducing a small step change in the particular forcing function-- steam control valve stem position, feed flow rate and reflux flow rate.

It was observed that the step size had to be restricted below 5 percent to obtain results which agreed with the pulse test results. Another limitation was the period over which the step response was measured; this had to be kept within 20-25 minutes. Longer periods introduced errors due to drift and unobserved forcings. Larger step sizes showed higher steady state gain, indicating the effects of the non-linearity of the system.

SINUSOIDAL TESTING:

As the response of the feed and the reflux control valves (flow rates) to sinusoidal forcings on the air signal to the control valves was far from sinusoidal, no attempt could be made to experimentally verify the results of the pulse test for forcings on the feed and the reflux flow rates, using sinusoidal testing technique.

However the response of the steam control valve (stem position) to sinusoidal forcing on the air signal to the valve was nearly sinusoidal. Continuous sinusoidal air signals of different frequency and amplitude were generated using the combination of Function Generator models 3300 A and 3301A

coupled with Swartout Autoronic transducer. The forcing was done for sufficient time to attain steady state gain. The steam control valve stem position was then recorded as input and the particular tray temperature as output. From these the gain and phase lag for different trays at different frequencies were computed and were compared with those obtained from the pulse test data. The peak to peak amplitude of the forcing sine wave was equal to the corresponding peak height of the input pulse.

Pulse Test on Control Valves:

A triangular pulse was forced on the air signal to each feed and steam control valve and the response recorded was feed flow rate and steam control valve stem position respectively. No pulse test was conducted on the reflux control valve due to peculiar mechanical friction in the valve, as mentioned earlier in this chapter.

CHAPTER V

REDUCTION OF EXPERIMENTAL DATA

The experimental data of the pulse test were reduced to frequency response data using the numerical integration technique programmed on IBM 360/65 computer.

The original program computed $G(j\omega)$ as per equation (C. 1.7) and obtained Dynamic Amplitude Ratio, DAR, and Dynamic Response Angle, DRA, using the basic equations (3.3.1) through (3.3.10).

However, due to the decrease in amplitude of Fourier transform of the input pulse at higher frequencies, slight drifts in the output transform showed large effects in DAR. Similar difficulty was observed by Banham, Jr., (40) while reducing the pulse test data obtained on steam generating systems. To avoid fluctuations, individual Fourier transforms (amplitudes and angles) of both response and input pulses were computed and then plotted separately on the same graph. Smooth curves were drawn for both, neglecting small fluctuations in the response transform, particularly at higher frequencies. From these curves of input and response transforms, DAR and DRA were obtained by hand, as the method reduces to subtraction of the input curve from the response curve on the Bode logarithmic graphs. The method is indicated in detail in figures 7 and 8 to obtain frequency response of tray 4 to forcing on the reflux.

To observe the effect due to data-reading error, scattered error of ± 0.1 mm was introduced over a uniform interval in the response curve data. The resulting error due to it ranged from 0.2 percent maximum at low frequency to 0.5 percent maximum at high frequency for cases having a peak response of over 6 mm.

The computer program was based on two time intervals for each input and response curve. The two time intervals chosen for the response curve were 5 and 10 seconds. However to yield better results the computer program was altered to numerically reduce the response data at 2.5 second intervals and calculate the response Fourier transform based on the reduced data. The numerical reduction of the original data with the higher time interval, to one with lower time interval was based upon the assumption of straight line segments between the original data time intervals. The response curve did meet this requirement, particularly in the decay zero.

The frequency response obtained with this modification was smoother and at high frequencies differed with that computed with the larger time interval. Since the computer program incorporated the modification suggested by Hougen and Walsh (29) to evaluate $G(j\omega)$ using equation (C.1.7), the findings of the author did not agree with them. Hougen and Walsh stated that the above equation would give the exact transform when applied to a pulse composed of straight line segments, if the segment boundaries coincide with the interval

boundries.

Finally the main program was coupled with a subroutine program to compute the lag window function associated with response curves obtained for forcings on steam. With this corrected response was obtained using equation (3.5.3).

In appendix C the computer program, incorporating all the features indicated above, is given.

In figures 7 through 15 the frequency response, in the form of Bode diagram, of the temperature of different trays for forcings on the reflux flow rate are presented. Only in figure 7 and 8 the method of obtaining gain and phase lag from the separate Fourier transforms of the input and response functions is illustrated.

The frequency response of trays 6,8,9 and 10, for forcings on the feed flow rate, is presented in figures 16 through 19.

The frequency response of trays 10,9,8,6,4,3,2 and 1, for forcings on steam, is presented in figures 20 through 28. The frequency response for this case was computed using the lag window function with the response data. However to compare the effect of the lag window function, the gain curve presented in figure 23 and the phase lag curve, presented in figure 24, of the frequency response of tray 6 includes the response computed without treating the output pulse data with the lag window function.

Finally, the figure 29 presents the frequency response of

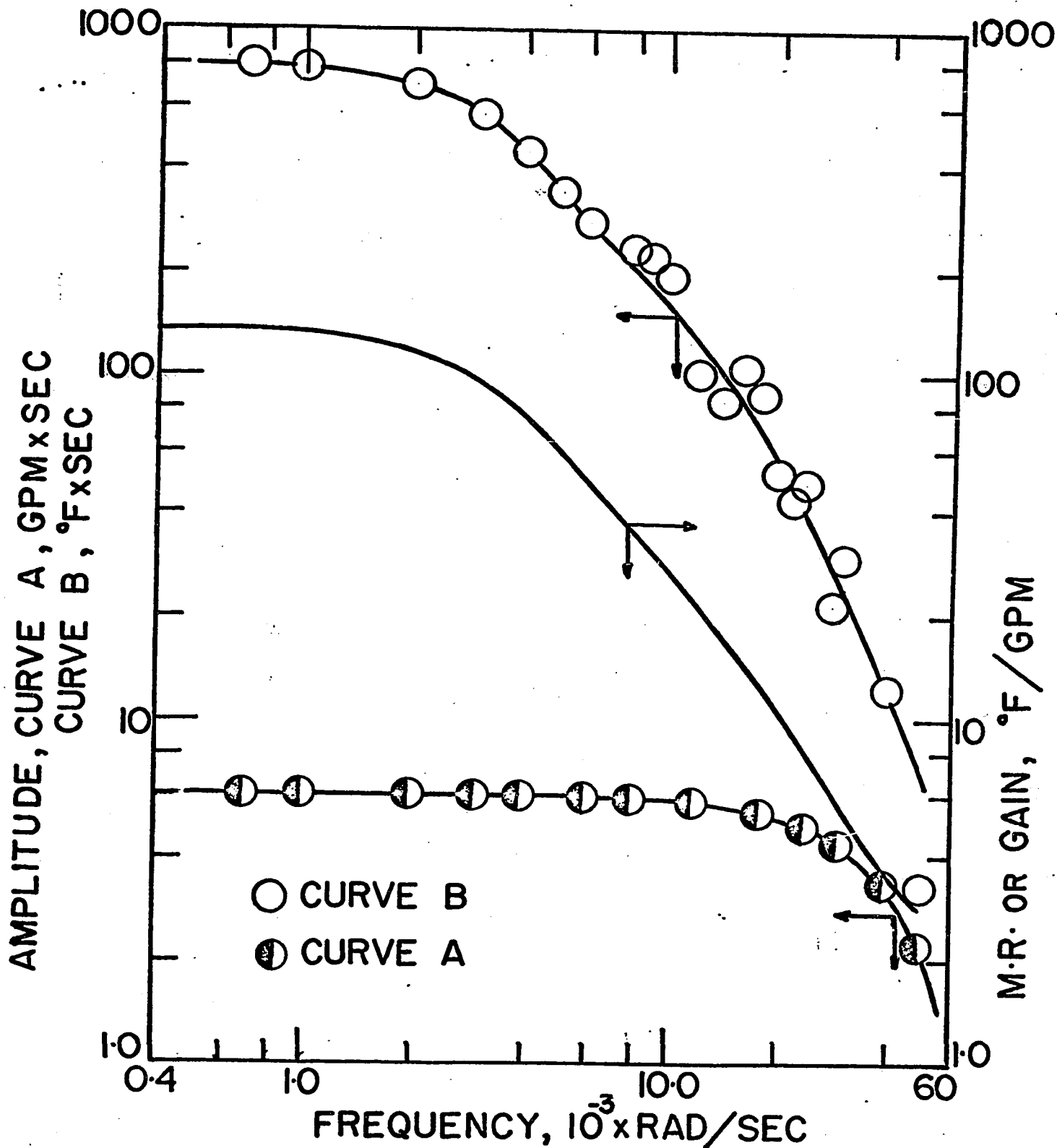


Figure 7. Frequency Response (Gain only) of the Temperature of Tray 4 to the forcing on the Reflux flow rate.

The system Gain curve is obtained by graphical subtraction (on logarithmic scale) of amplitude (curve A) of input pulse Fourier transform from amplitude (curve B) of output pulse Fourier transform.

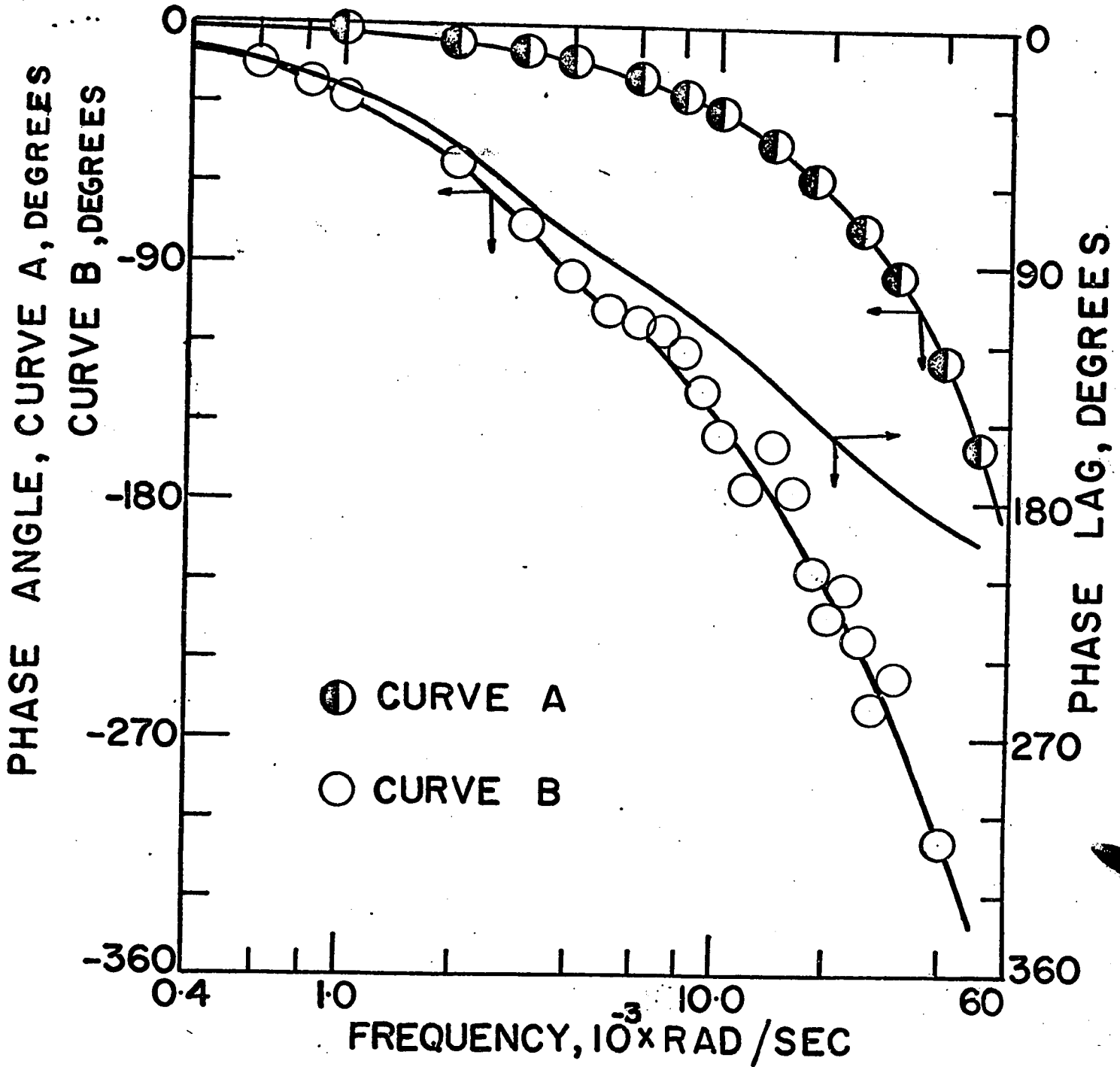


Figure 8. Frequency Response (Phase Lag only) of the temperature of Tray 4 to the forcing on the Reflux flow rate.

The system Phase Lag curve is obtained by graphical subtraction of phase angle (curve A) of input pulse Fourier transform from phase angle (curve B) of output pulse Fourier transform. Note the result, being written as phase lag, is written with positive sign.

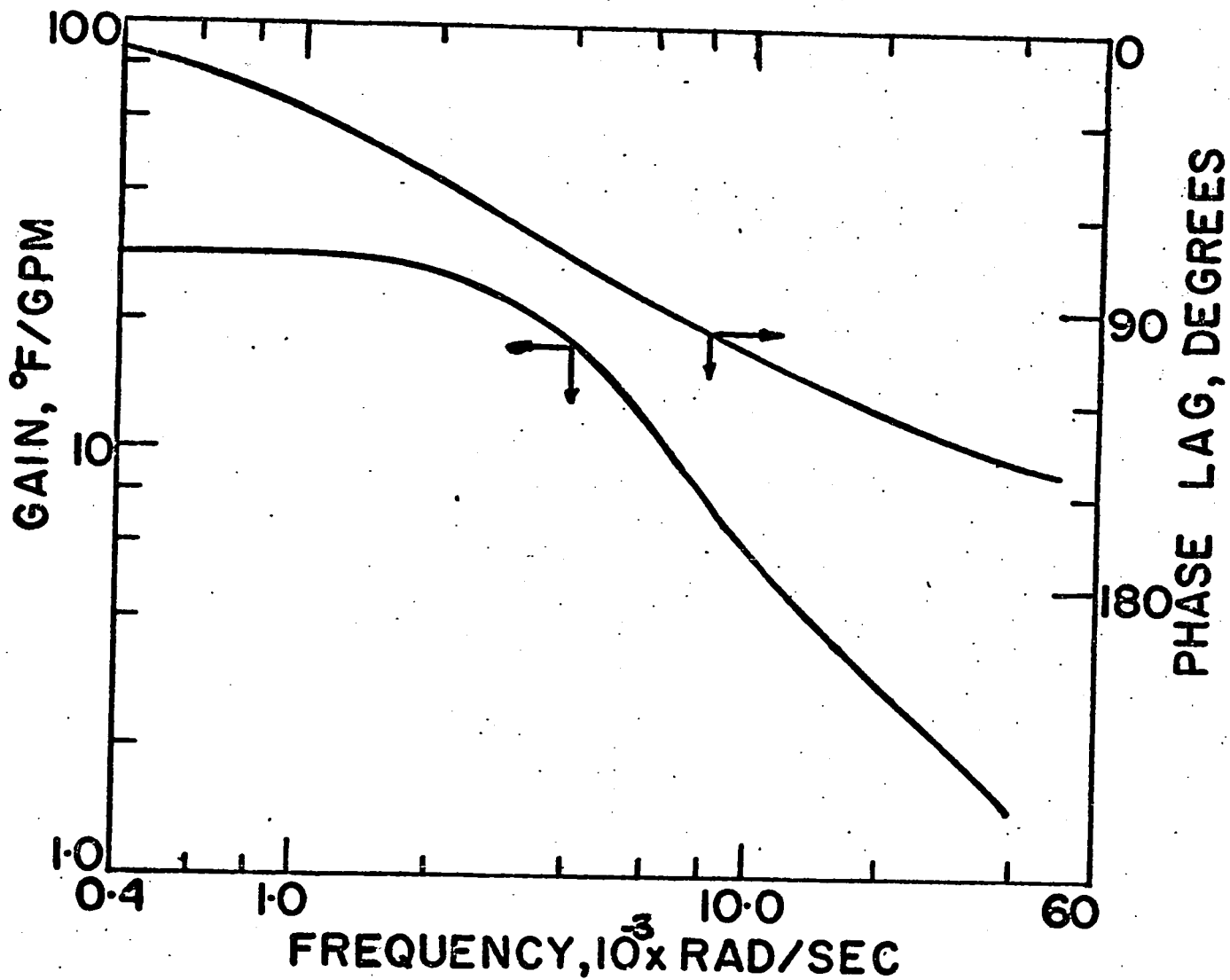


Figure 9. Frequency Response of the Temperature of Tray 1 to the forcing on the Reflux flow rate.

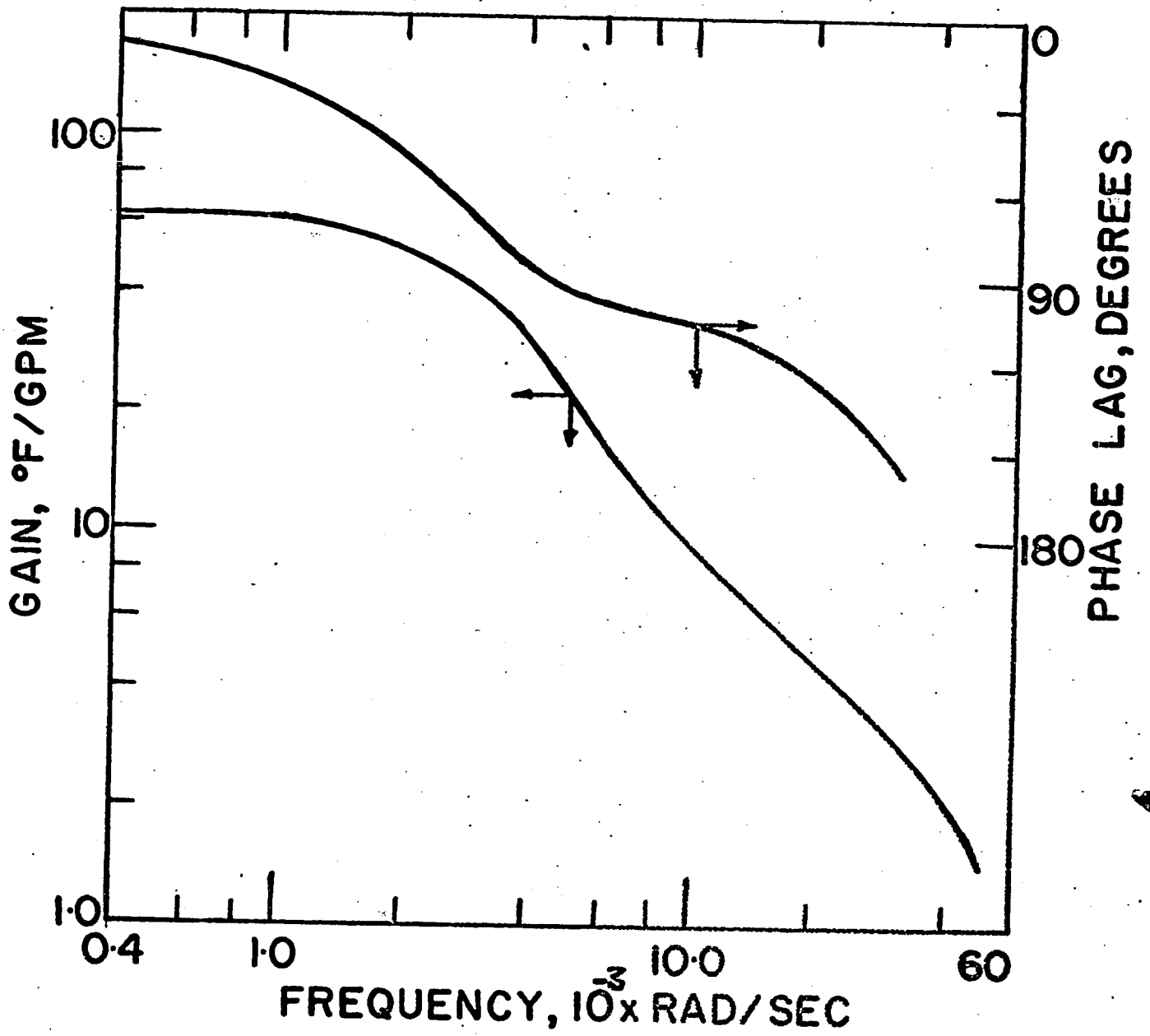


Figure 10. Frequency response of the Temperature of Tray 2 to the forcing on the Reflux flow rate.

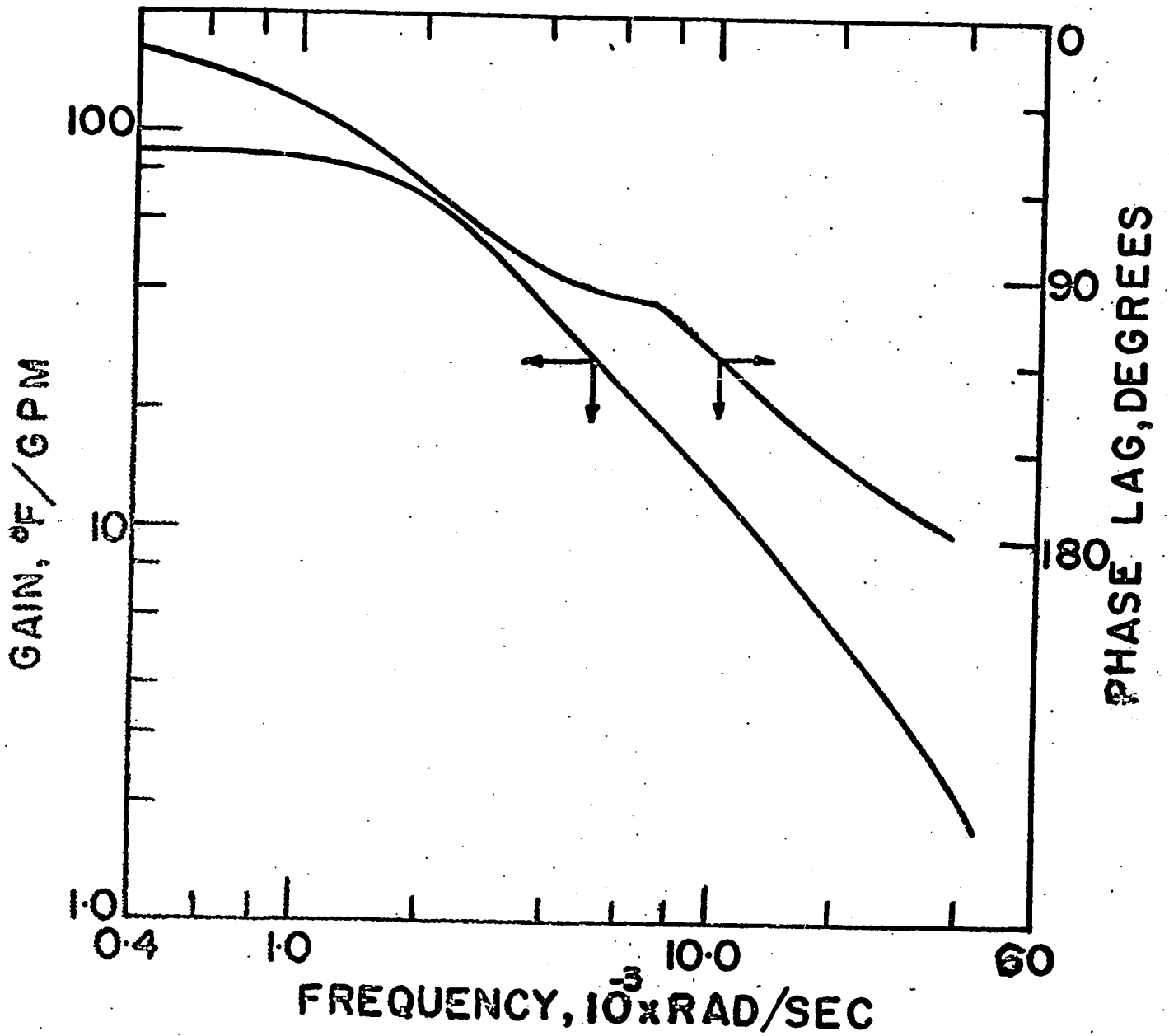


Figure 11. Frequency Response of the Temperature of Tray 3 to the forcing on the Reflux flow rate.

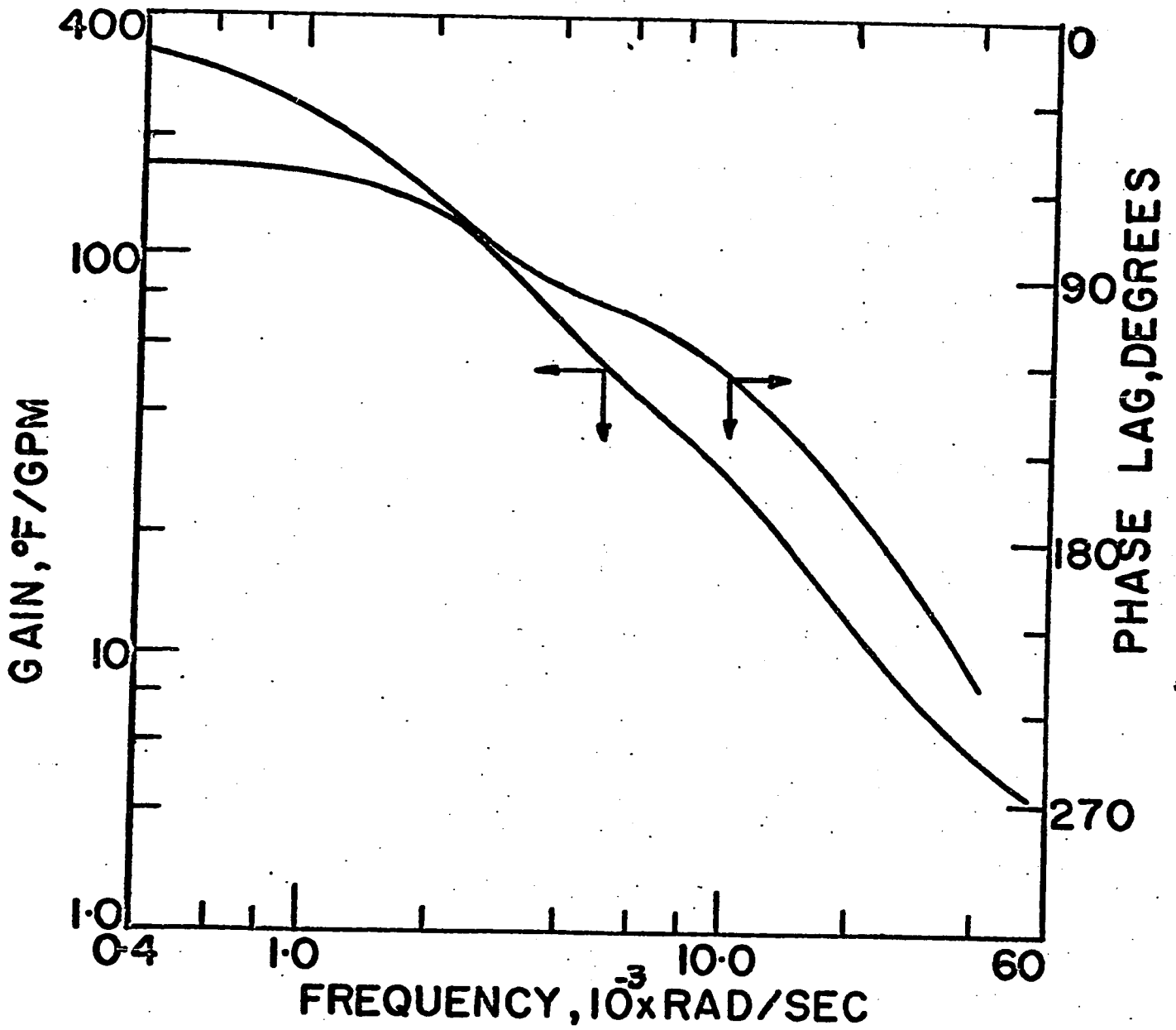


Figure 12. Frequency Response of the Temperature of Tray 6 to the forcing on the Reflux flow rate.

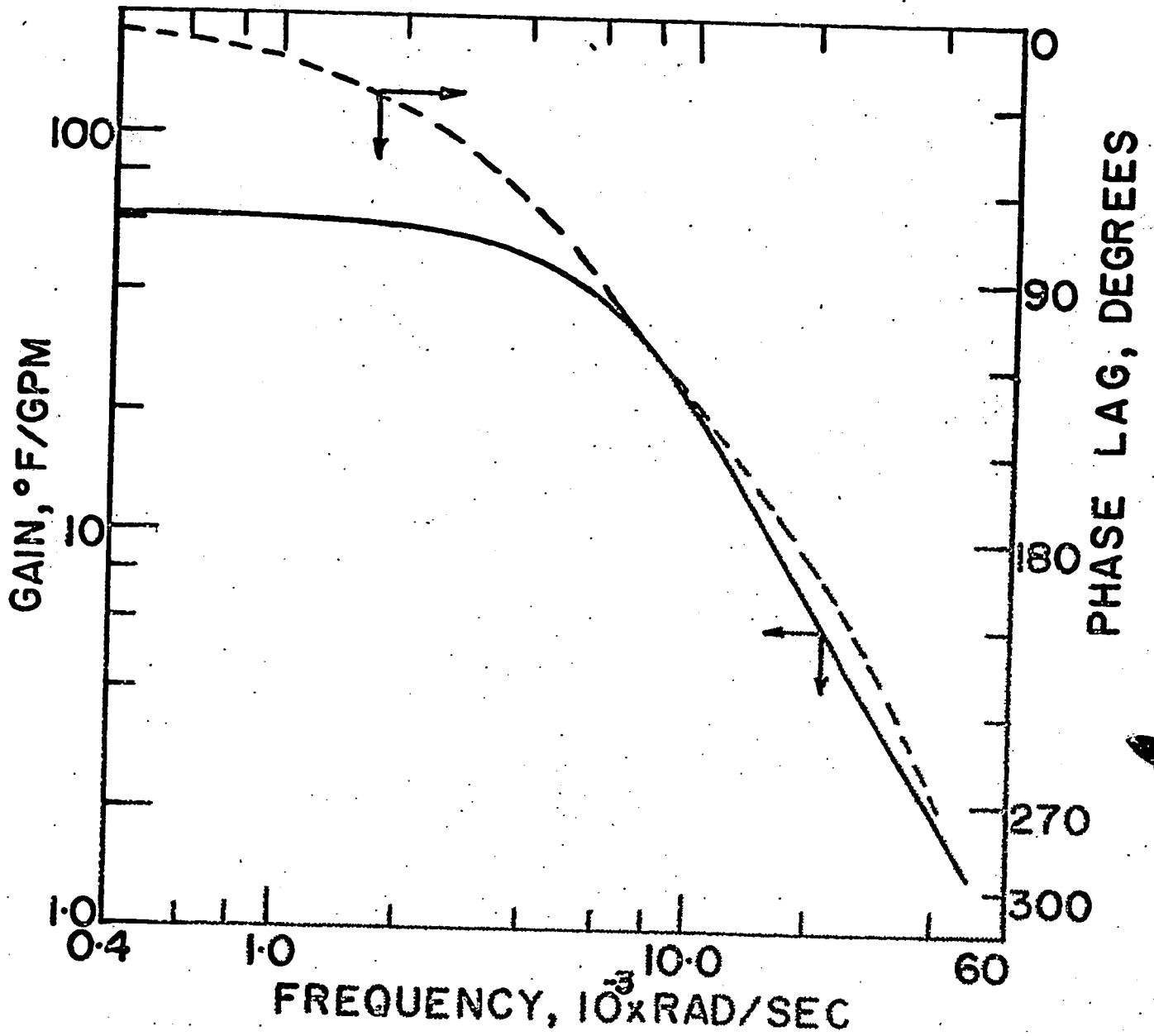


Figure 13. Frequency Response of the Temperature of Tray 8 to the forcing on the Reflux flow rate.

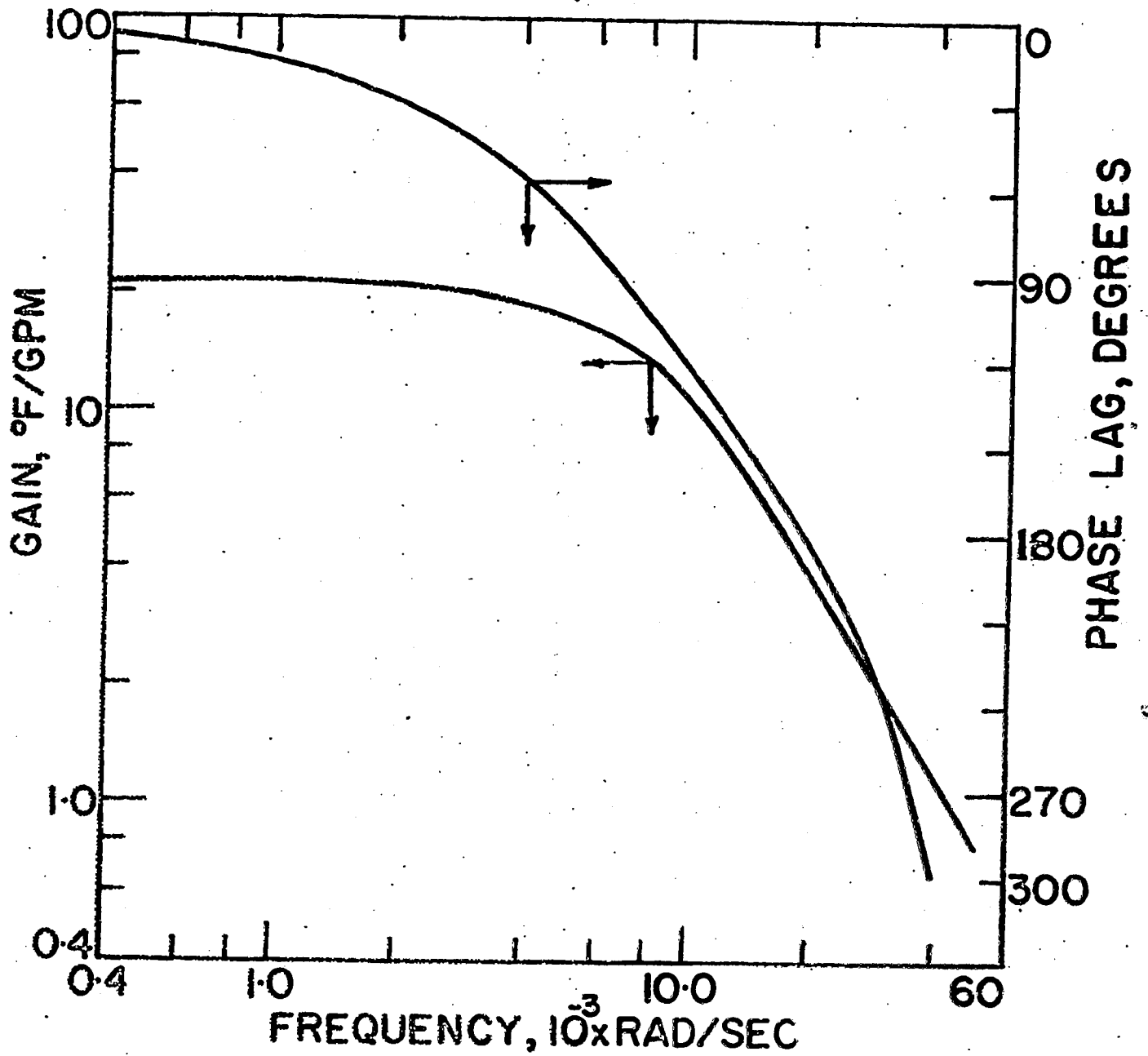


Figure 14. Frequency Response of the Temperature of Tray 9 to the forcing on the Reflux flow rate.

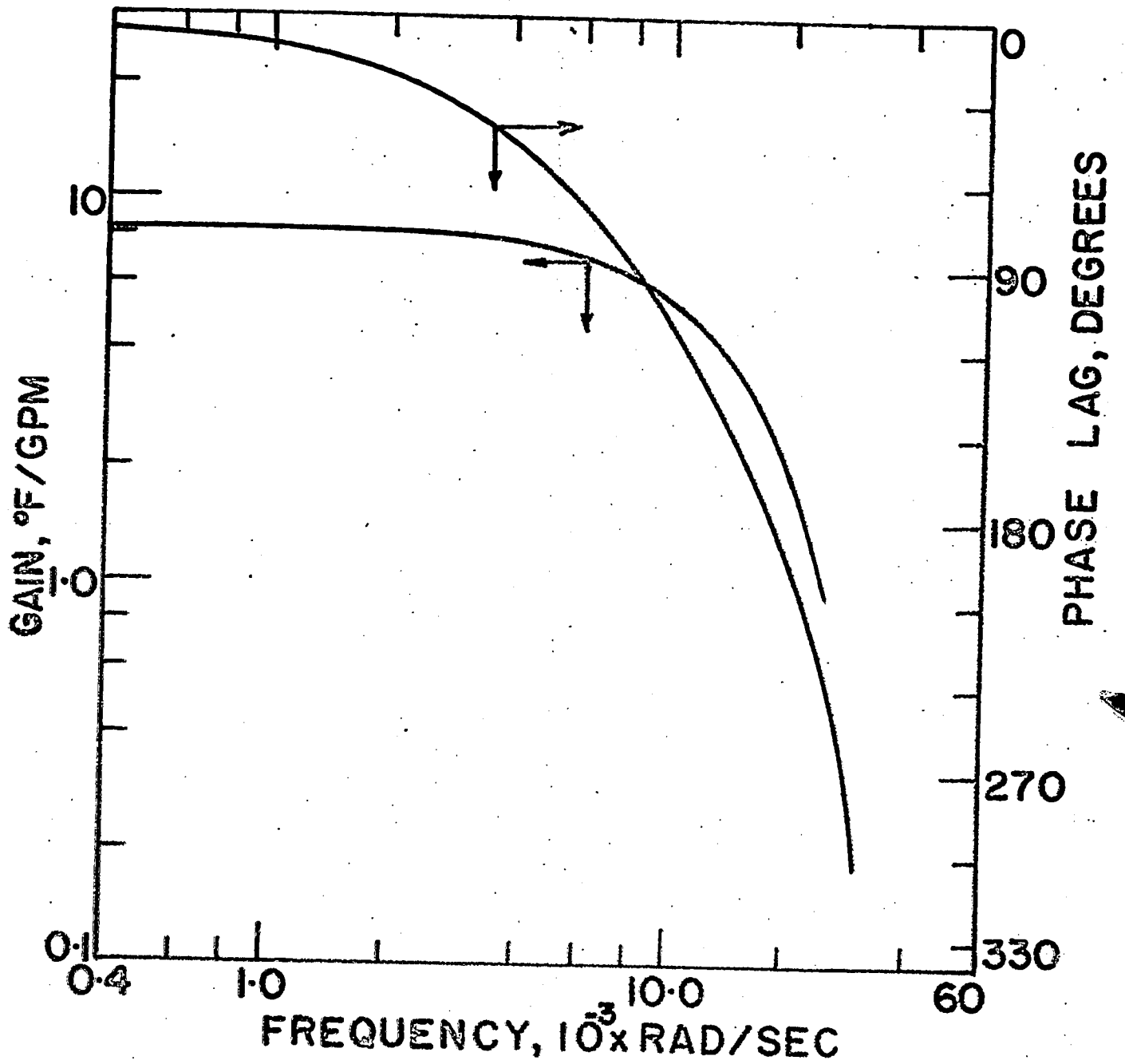


Figure 15. Frequency Response of the Temperature of Tray 10 to the forcing on the Reflux flow rate.

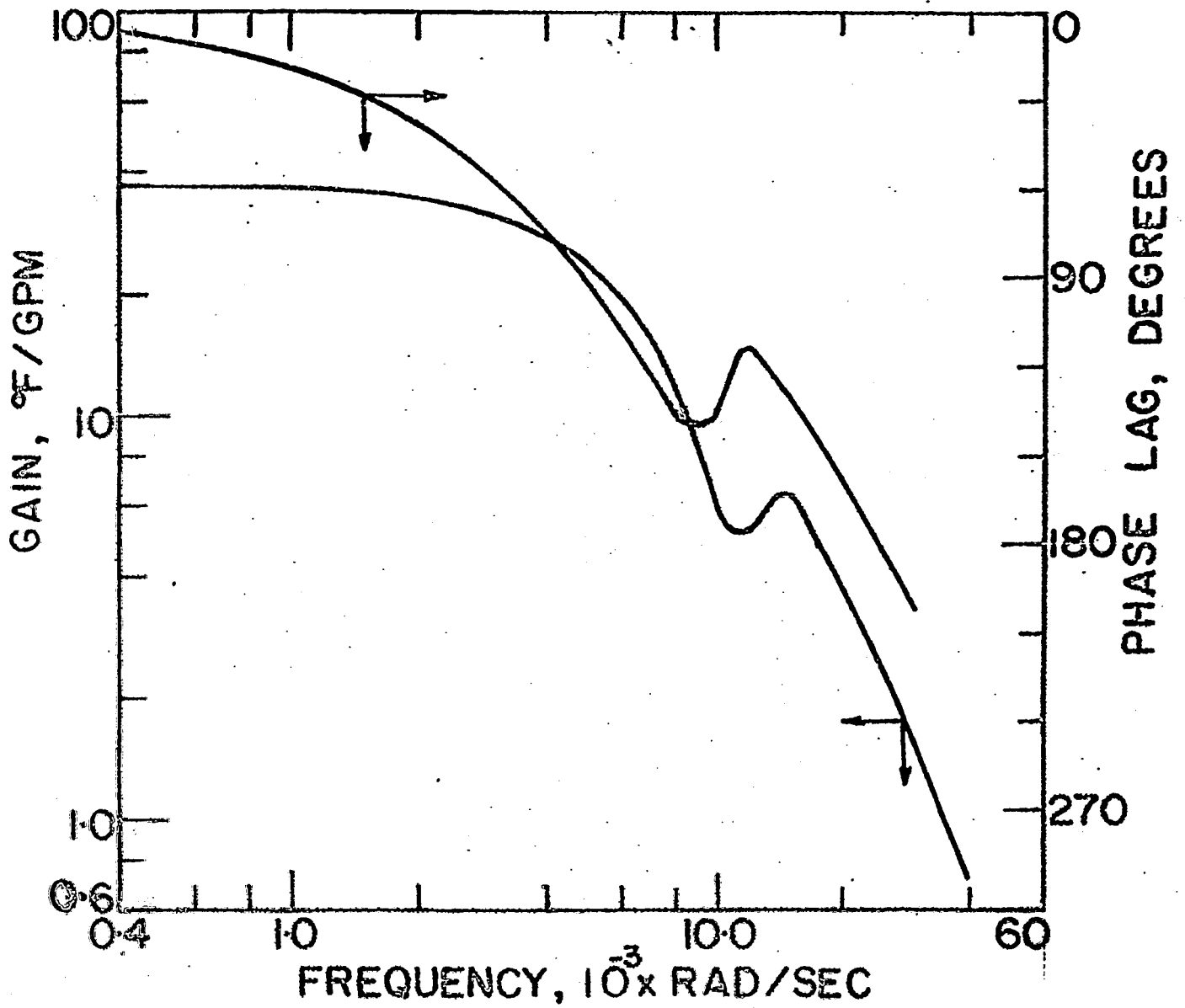


Figure 16. Frequency Response of the Temperature of Tray 6 to the forcing on the Feed flow rate.

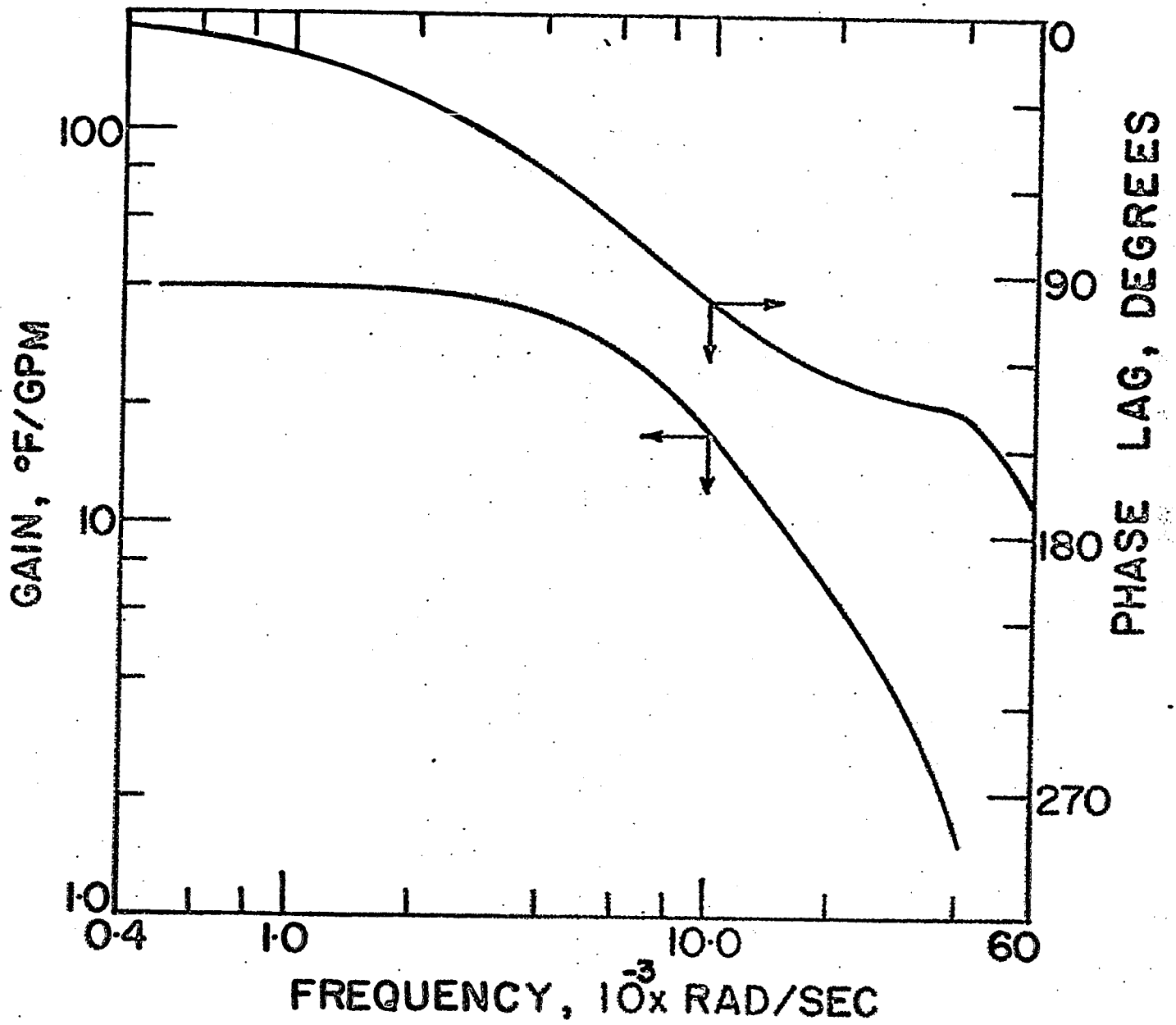


Figure 17. Frequency Response of the Temperature of Tray 8 to the forcing on the Feed flow rate.

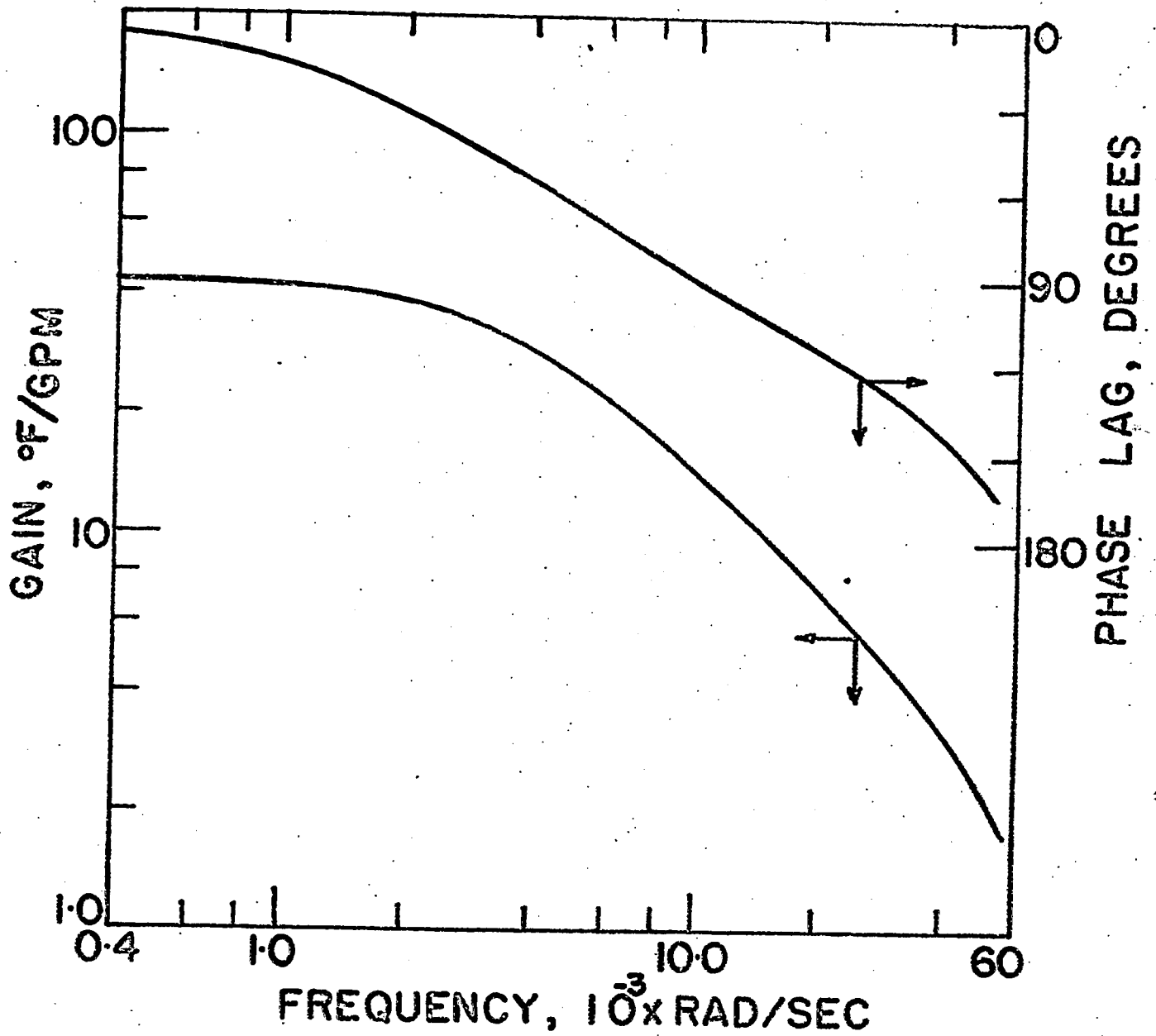


Figure 18. Frequency Response of the Temperature of Tray 9 to the forcing on the Feed flow rate.

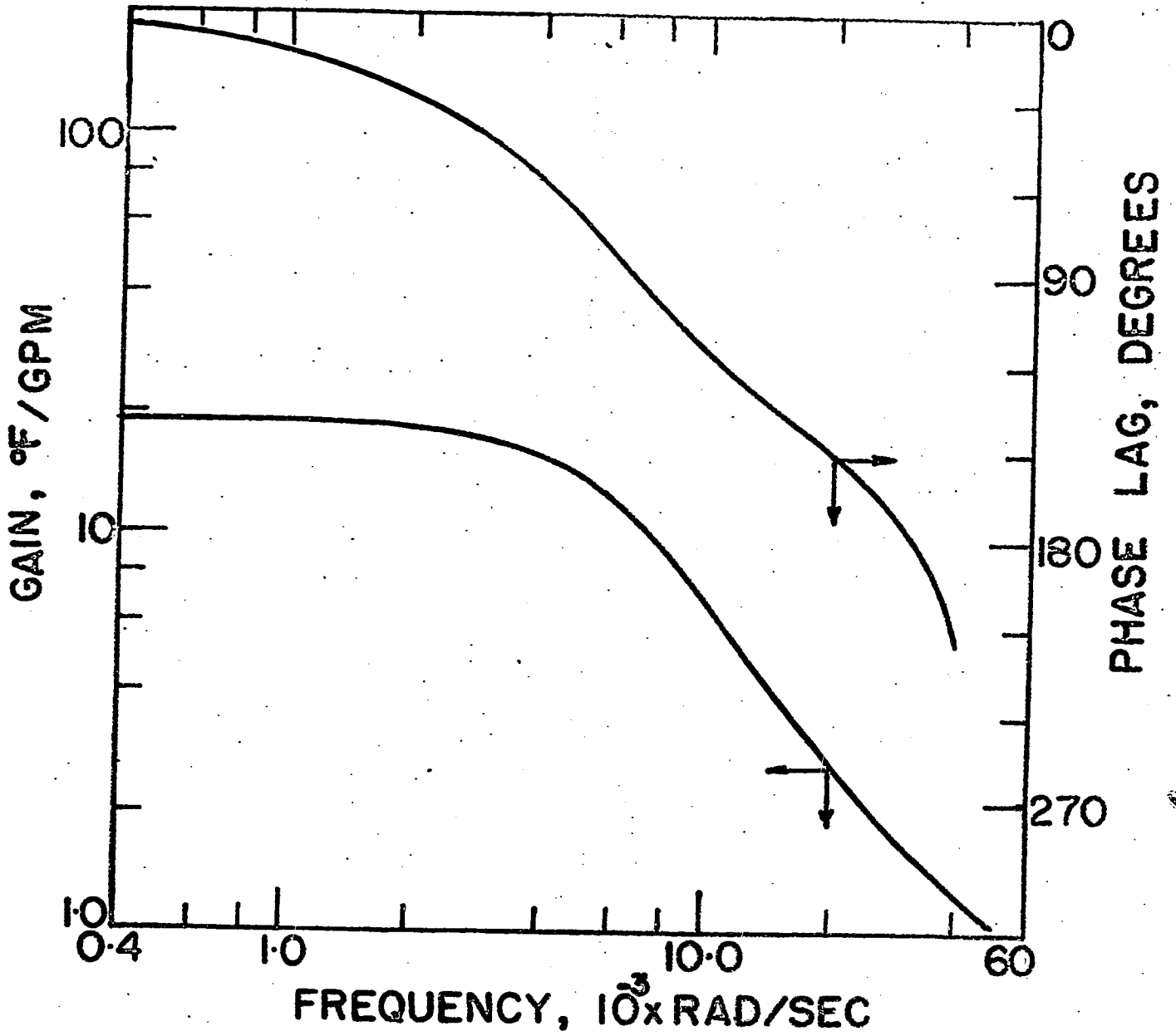


Figure 19. Frequency Response of the Temperature of Tray 10 to the forcing on the Feed flow rate.

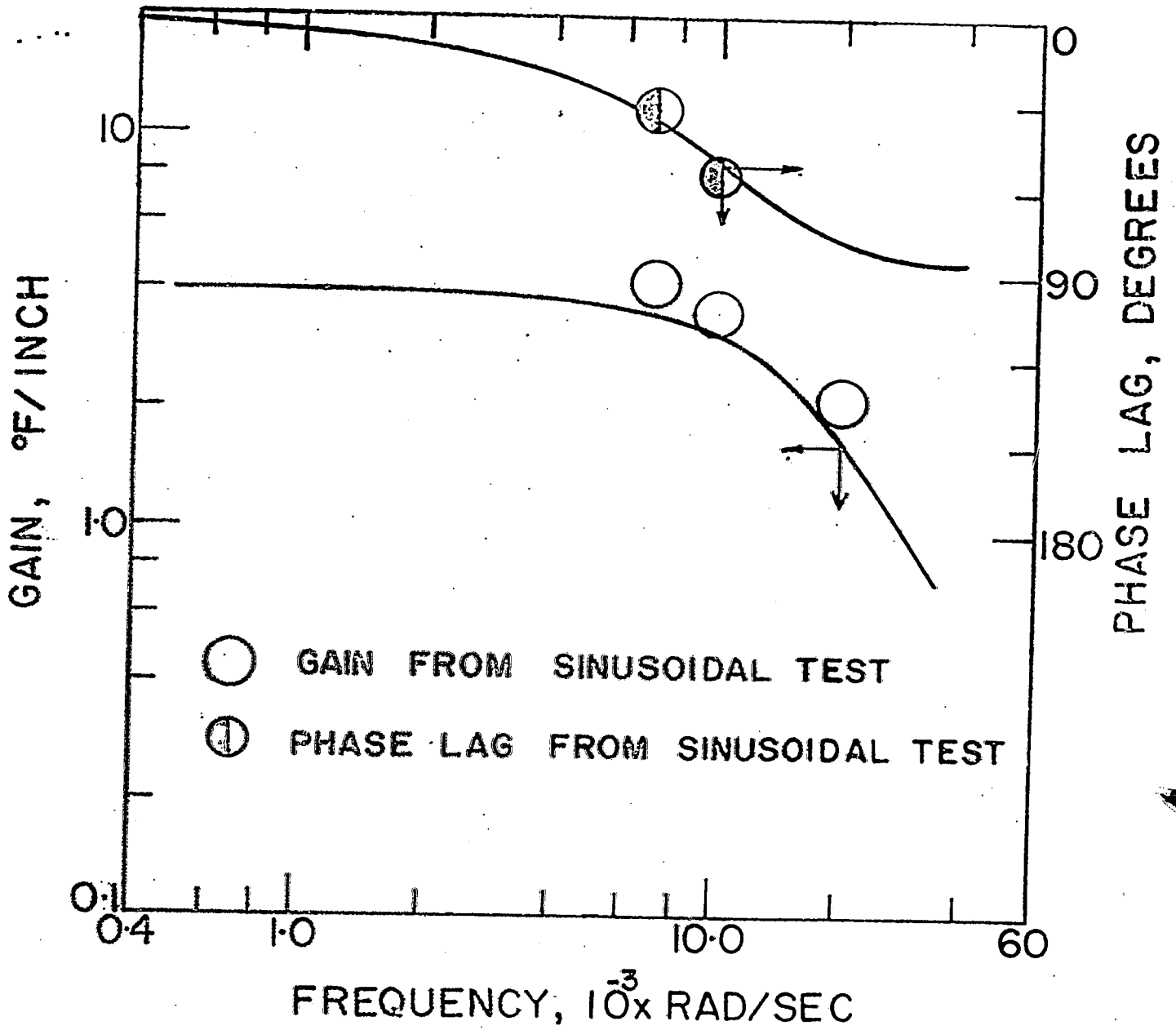


Figure 20. Frequency Response of the Temperature of Tray 10 to the forcing on the Steam.

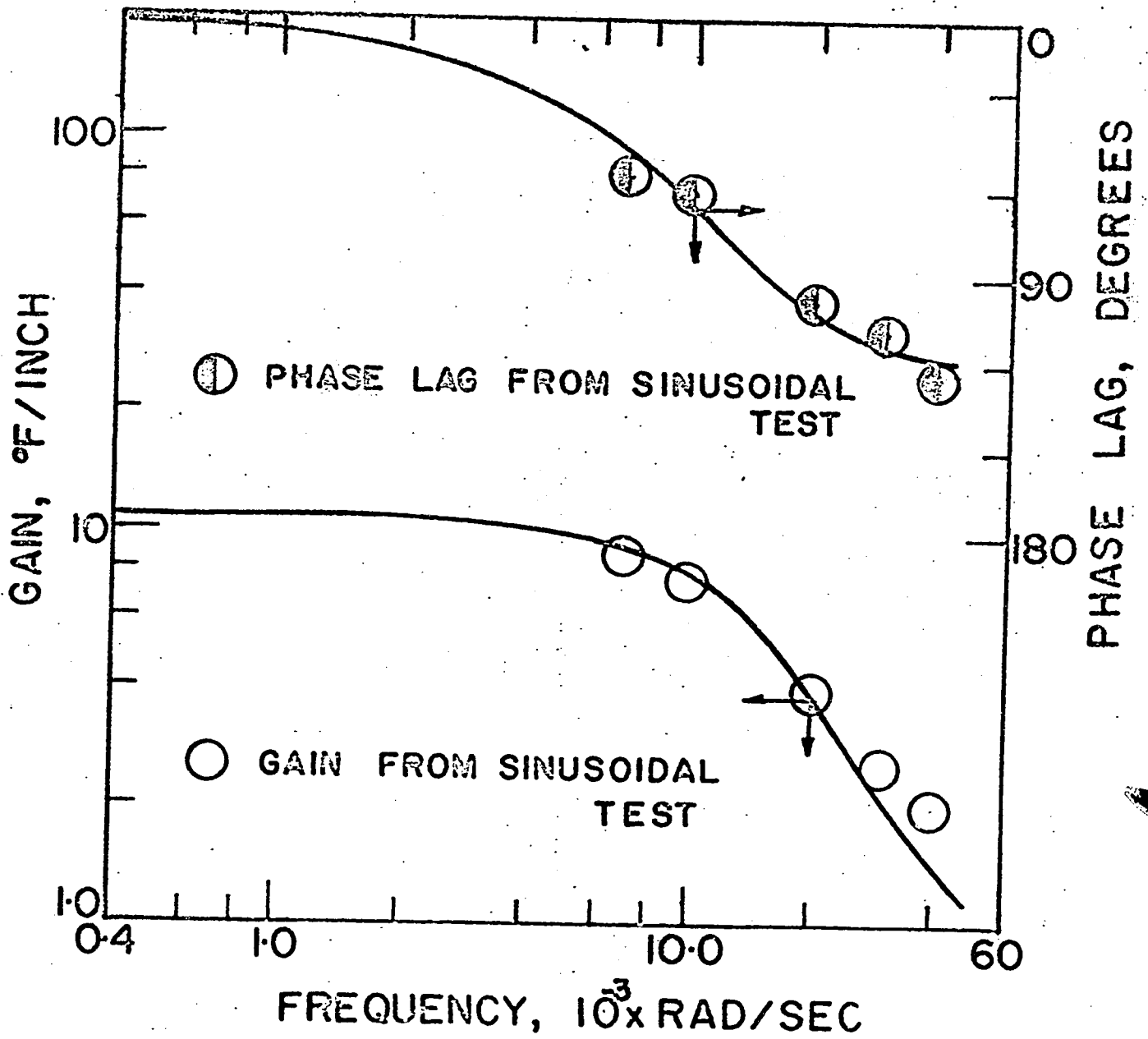


Figure 21. Frequency Response of the Temperature of Tray 9 to the forcing on the Steam.

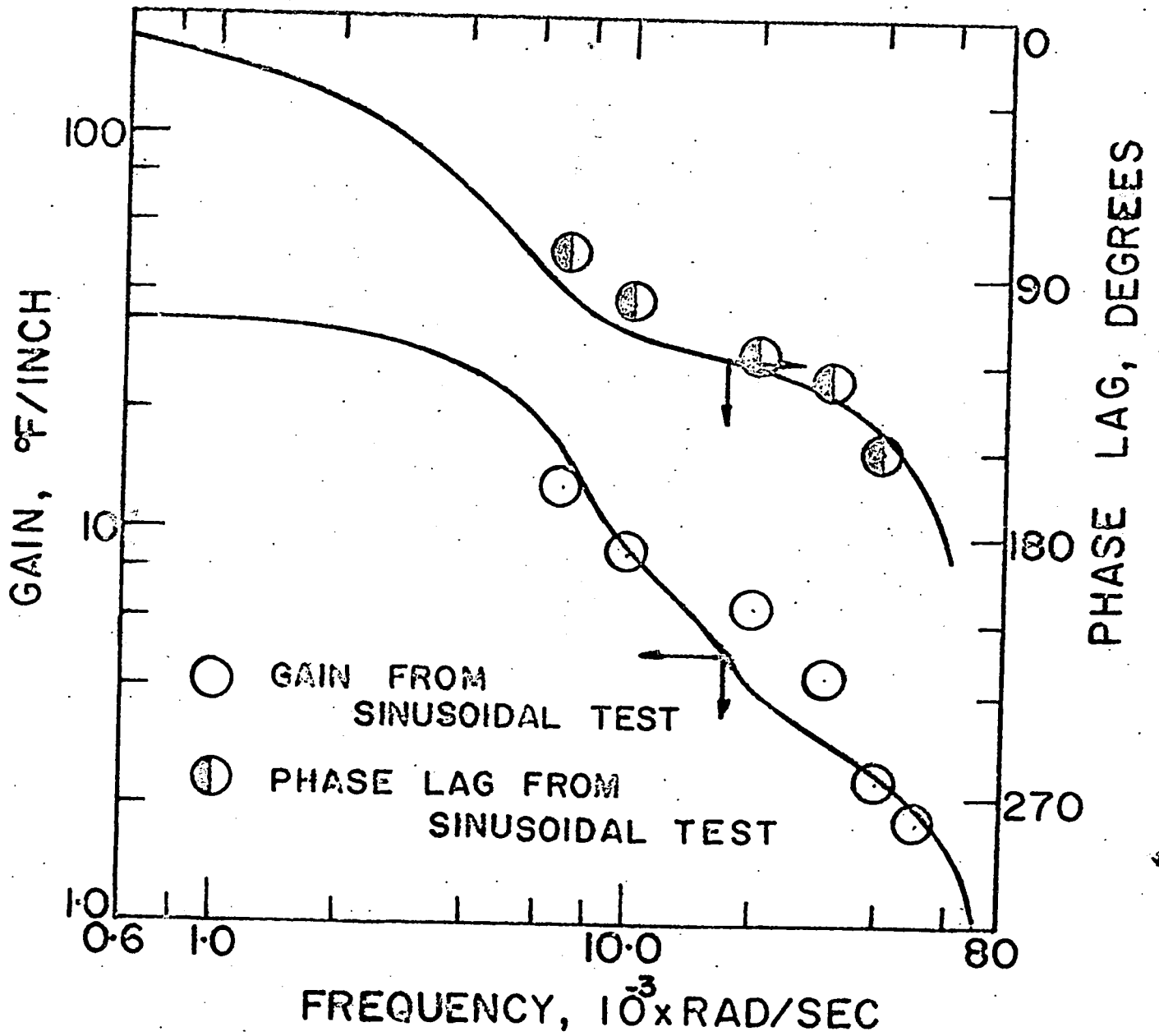


Figure 22. Frequency Response of the Temperature of Tray 8 to the forcing on the Steam.

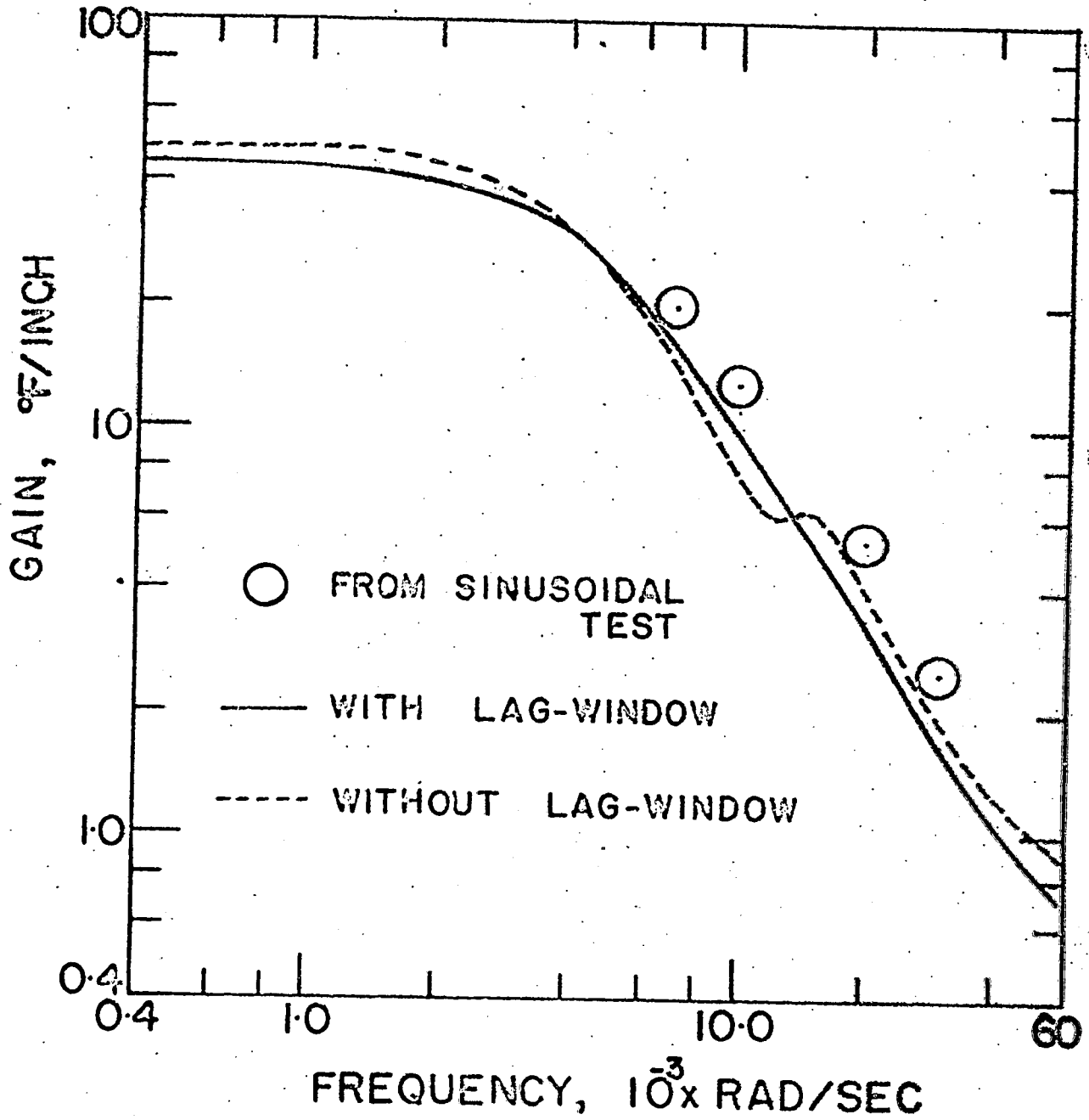


Figure 23. Frequency Response (Gain), with and without use of Lag-window function, of the Temperature of Tray 6 to the forcing on the Steam.

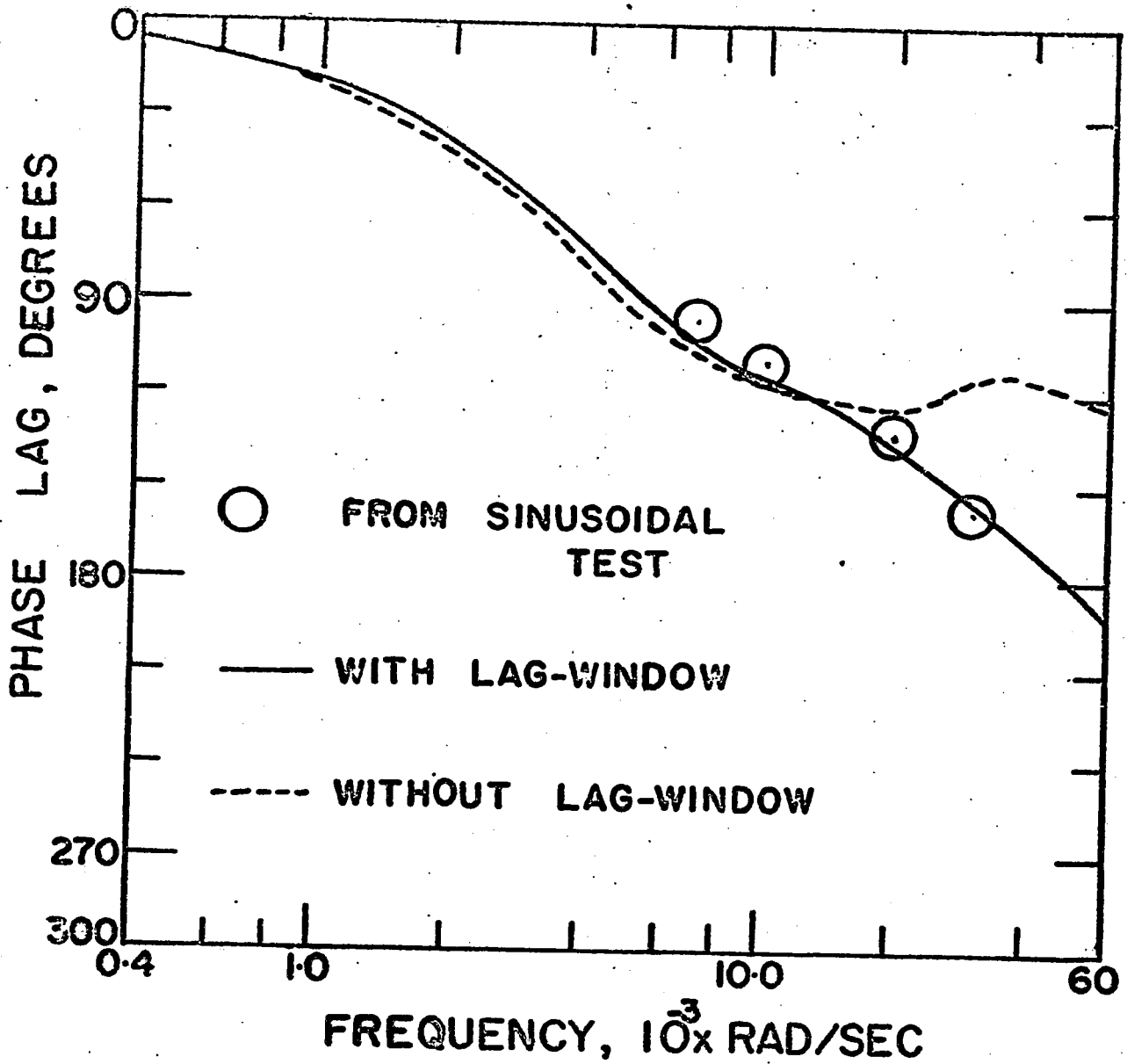


Figure 24. Frequency Response (Phase Lag), with and without use of Lag-window function, of the Temperature of Tray 6 to the forcing on the Steam.

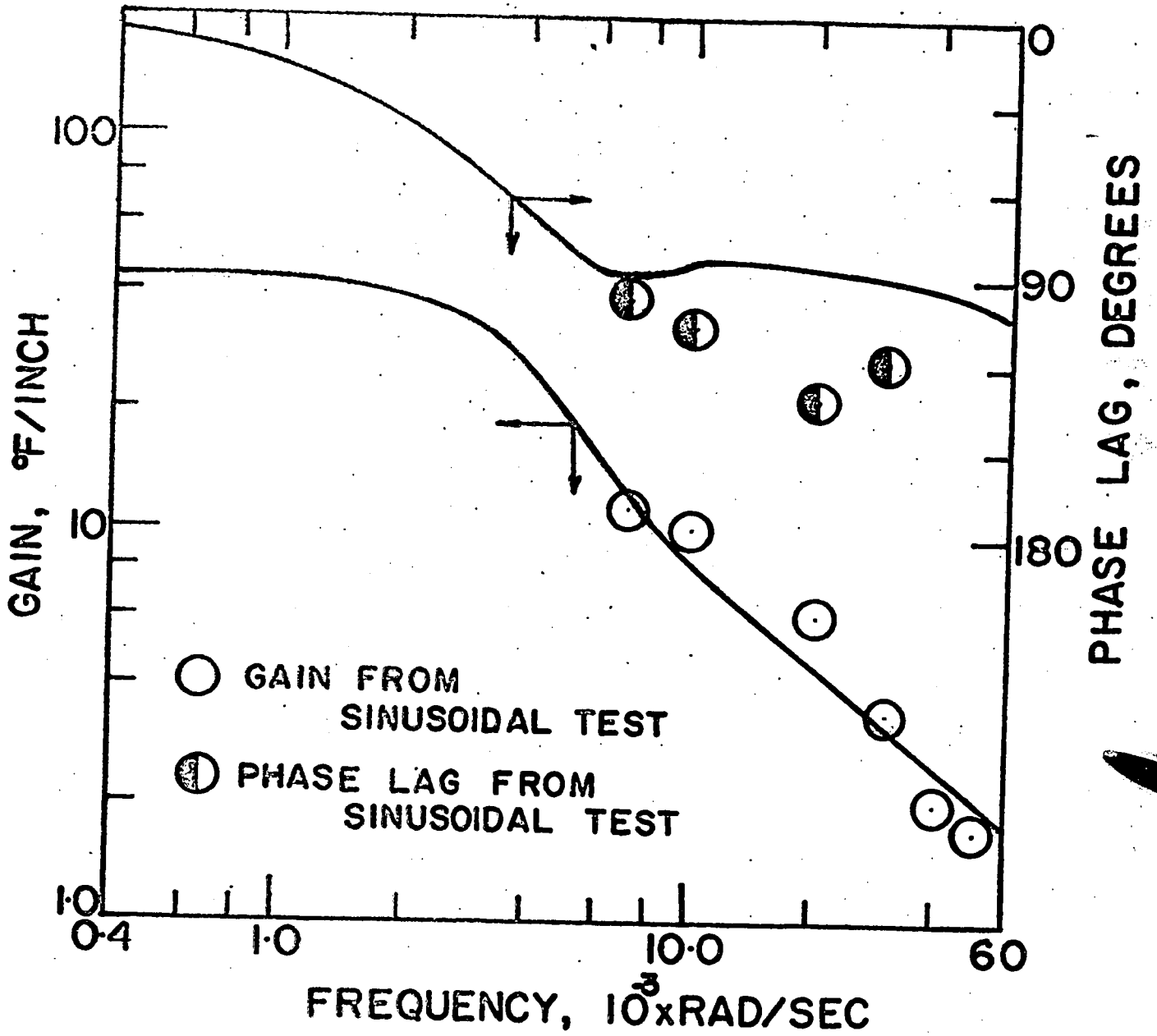


Figure 25. Frequency Response of the Temperature of Tray 4 to the forcing on the Steam.

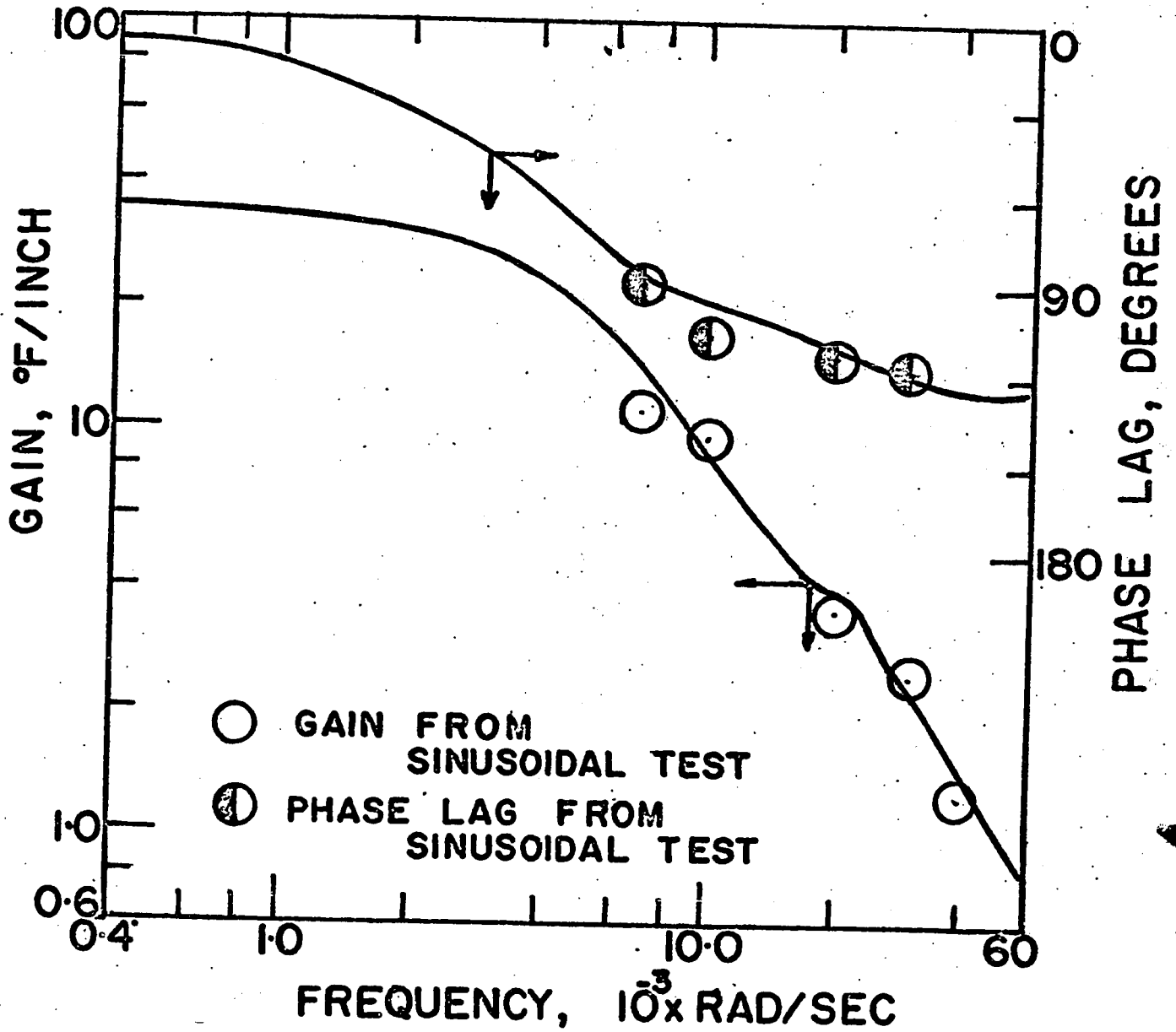


Figure 26. Frequency Response of the Temperature of Tray 3 to the forcing on the Steam.

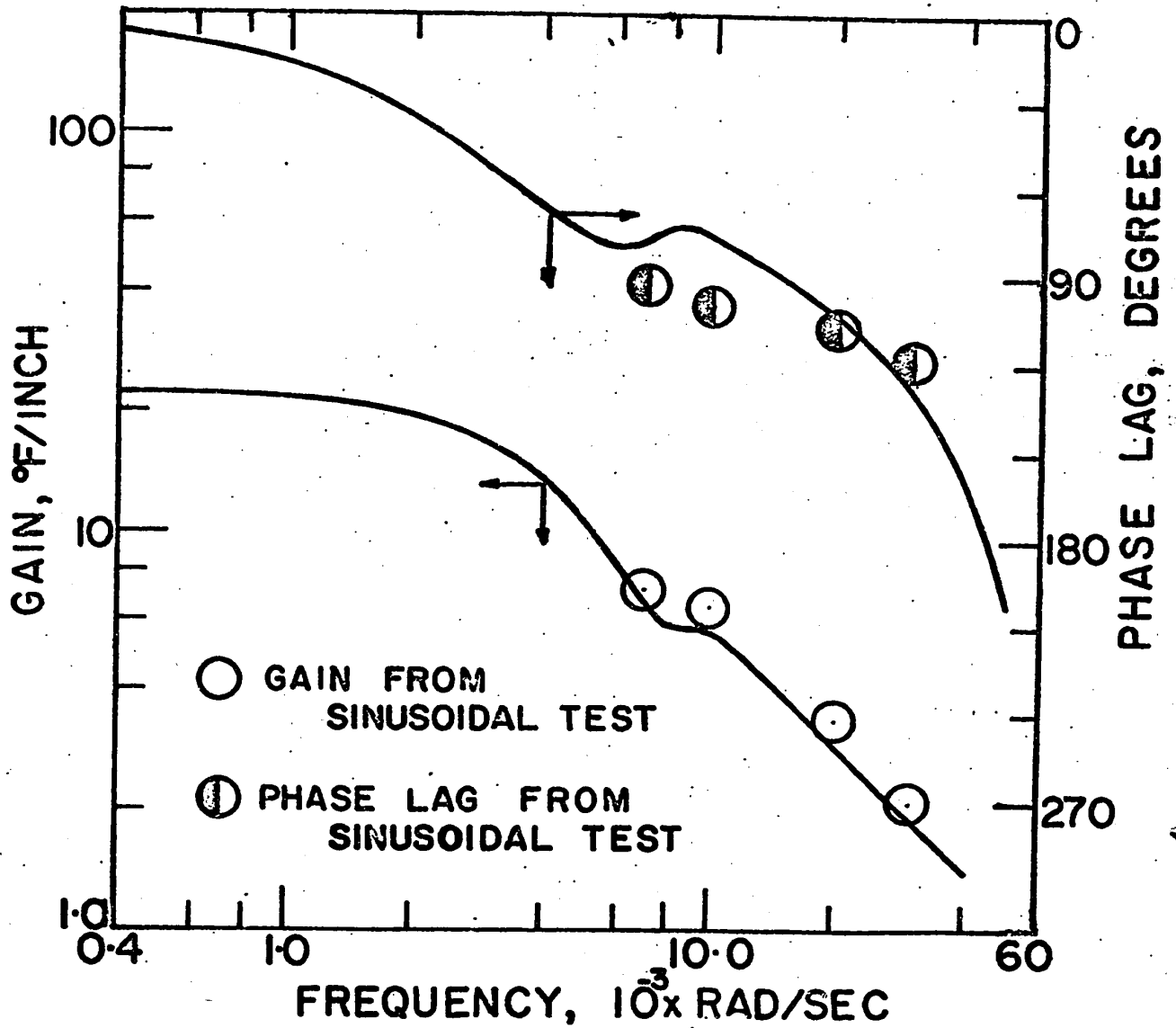


Figure 27. Frequency Response of the Temperature of Tray 2 to the forcing on the Steam.

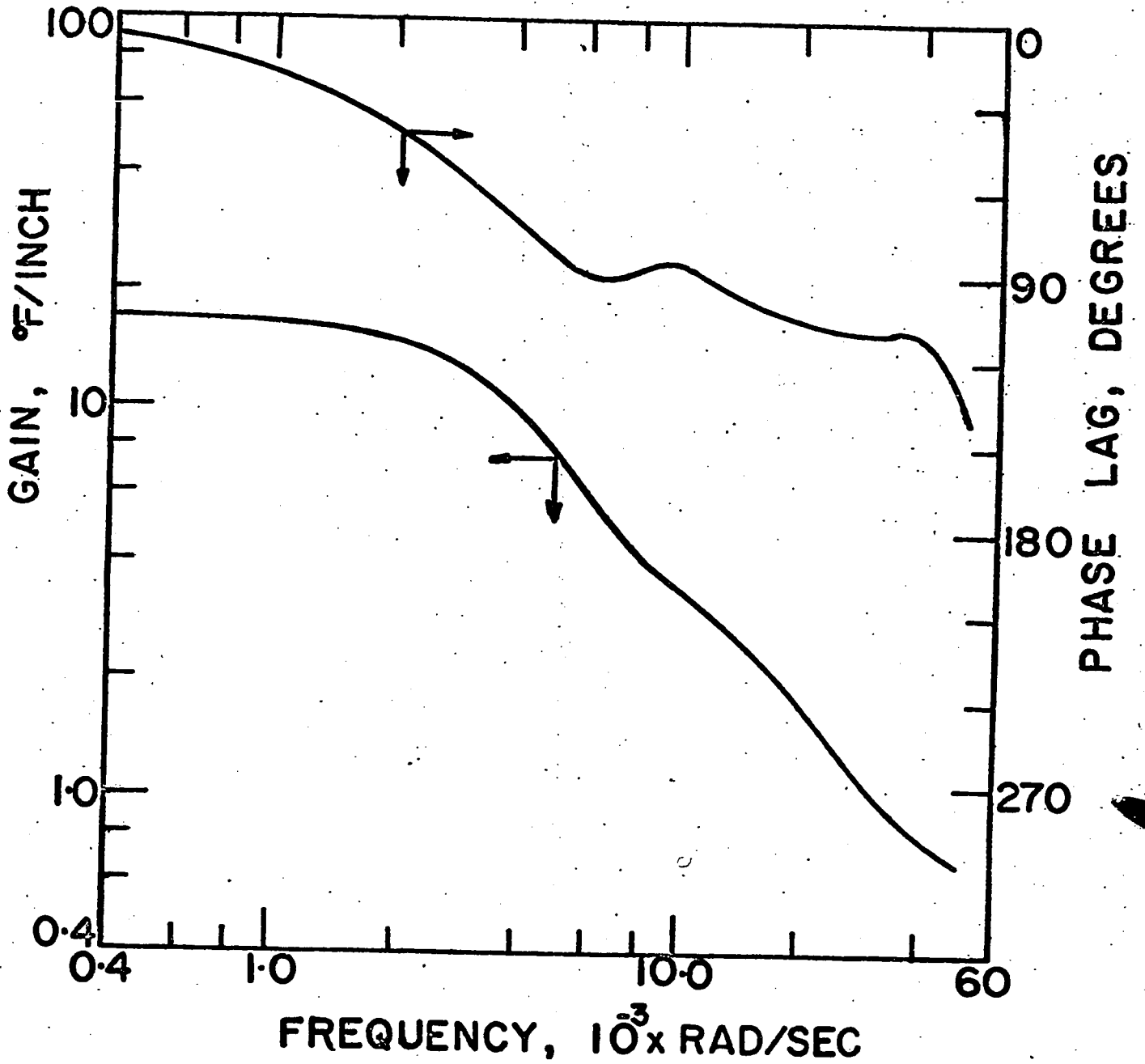


Figure 28. Frequency Response of the Temperature of Tray 1 to the forcing on the Steam.

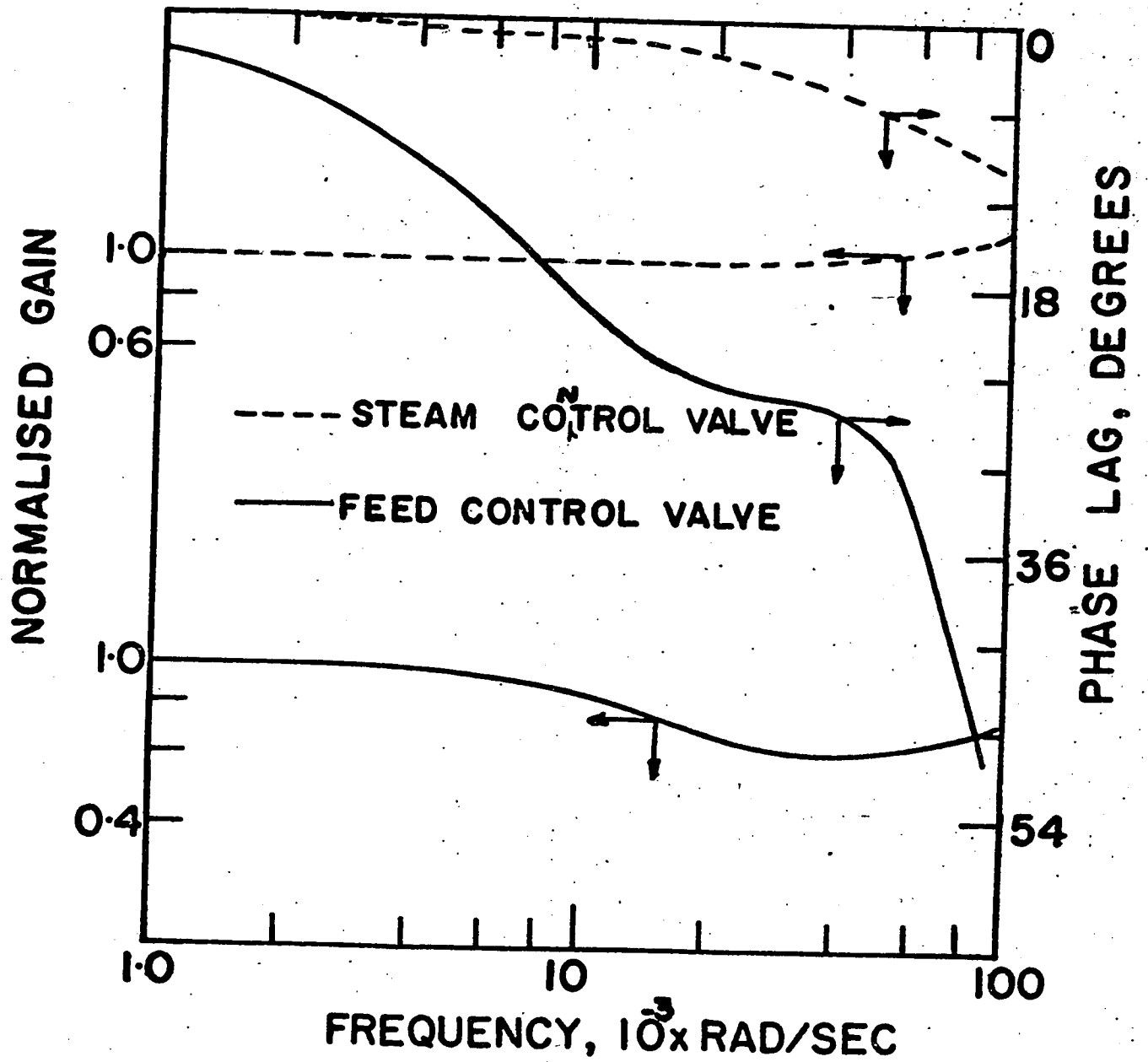


Figure 29. Frequency Response of the Steam and Feed control valves.

feed and steam control valves over the range of interested frequencies. The input pulse is on air-signal to the control valve while the output pulse is feed flow rate, in case of the feed control valve, and the valve-stem position, in case of the steam control valve.

The steady-state gains obtained with the pulse test and the step test are tabulated in appendix D.

The frequency response for different trays for sinusoidal forcings at a few frequencies (in the range of interest) for steam forcing is included in figures 20 through 27. For comparison between the frequency response obtained with the pulse test, the values are presented in table 25 in appendix D.

From the frequency response curves obtained, the major time constants were computed graphically. All the trays showed only one first order major time constant, except the tray 10 (for forcing on reflux) and tray 6 (for forcing on feed), which showed two major time constants (first order). The above results were verified by machine computation, using a program for second order fitting of the gain curves by a regression technique (51). Both the results are presented in table 1.

TABLE 1

Major Time Constants for different Trays for
respective forcing on Reflux, Feed and Steam.

FORCING	TRAY	MAJOR TIME CONSTANTS, MINUTES		
		(by graph)	(by machine)	
REFLUX	1	7.2	7.2	
	2	7.6	7.7	
	3	8.3	8.9	
	4	7.6	7.6	
	6	8.3	8.7	
	8	4.0	4.1	
	9	3.2	3.2	
	10	2.6, 1.6	2.6, 1.6	
	FEED	6	4.6, 3.2	4.6, 3.2
		8	4.0	4.0
9		4.1	4.5	
10		3.6	3.8	
STEAM	1	7.0	7.0	
	2	7.0	7.0	
	3	5.7	5.7	
	4	7.0	7.0	
	6	6.0	6.0	
	8	4.1	4.3	
	9	2.1	2.1	
	10	1.9	1.9	

CHAPTER VI

DISCUSSION

The effect of the following data errors on the results obtained was studied.

TRUNCATION OF DATA:- Truncation of the output pulse is the sudden equating of the pulse to zero before it has actually reached this value. One might be tempted to alter the data in this manner when the output pulse has almost reached initial or steady state value and the data is decaying very slowly. The effect of this is to attenuate the low frequency part too sharply. As a result the steady state gain is reduced below its true value.

CURVE-READING Error:- It was found that with the response of over 6 mm (peak) on the chart, the effect due to uniformly scattered error, at regular intervals, of ± 0.1 mm over the original response data resulted in a maximum error in gain of 0.2 percent at low frequency to 0.5 percent at high frequency. Errors in phase lag were lower than this.

INSUFFICIENT CURVE READING:- With a very long response one is tempted to read less points on the curve (using larger time intervals). With modifications in the computer program, results could be obtained accurately, so long as over the chosen time interval the curve could be approximated by straight line segments. In the present investigation, this resulted

in the choice of 5 second (rise zone) and 10 second (decay zone) time intervals for the response curves. For the input pulse curve the chosen, time intervals were 2 and 2.5 seconds. SYSTEM Noise: The effect of system noise present in the response curve was to scatter the results over small bands of frequencies, which correspond to the frequency of the noise. These were partially eliminated by plotting individual Fourier transform of response and input pulse curves and drawing smooth lines through the response transform.

The effect of application of the lag window function (on responses to pulses on steam) was to cut off such noise functions in the response. The Fourier transform of such a reduced response curve was smoother. However as the lag window function was not unique, it also attenuated, besides noise, some of the true response from the recorded system response. This resulted in lowering the steady state gain from its true value. However it was found that in the frequency zone of primary interest, the gain obtained was nearly the same in both cases.

Hougen and Walsh (29) and Clements, Jr., (30) report that for most of the process systems good frequency response can be obtained down to 0.3 value of $s(\omega)_n$ of the input pulse. However, in the present investigation, small peak values were obtained for the response curves. This resulted in obtaining of good frequency response limited to 0.4 value of $s(\omega)_n$ of the input pulse. For cases of poor response the

frequency response results starting scattering at 0.5 value of $s(\omega)_n$.

The steady-state gain obtained from the pulse testing was in quite good agreement with that obtained from the step test. The size of the step test had to be kept very small at about 5 percent of the steady-state value, to obtain a good comparison between the two steady-state gains. At higher step sizes, the gain obtained was too high, indicating that the non-linearities of the system were excited. On the contrary the steady-state gain obtained with 20 to 25 percent peak height of an input pulse agreed with that obtained with a low step size of 5 percent. This indicated that the non-linearities of the column were not excited with a 20 to 25 percent pulse height.

For flow changes the non-linearity of a distillation column, neglecting fluid dynamics is due to the non-linear vapor-liquid equilibrium relation. However the vapor-liquid equilibrium curve of the methanol-water system is fairly linear at concentrations of methanol (in the liquid phase) of over 30 percent and in the low concentration range. From the results obtained there was only one major time constant for the trays. This was attributed to the mass transfer dynamics of the tray. The dynamics due to the flow of fluid over the trays had a relatively low time constant. Its effect was thus obtained only in phase lag curves and not in the gain curves. Thus during a pulse test hydraulic effects on the tray could

be neglected to the extent that the efficiency of each tray could be assumed to remain unchanged, resulting in a similar pseudo-equilibrium curve before, during and after the pulse test. Further the mass transfer lag over one plate did not seem to have considerable effect on the next plate, with the result that mass-transfer or concentration lag of each tray seemed to depend only on the concentration lag over the particular tray. This was contrary to the step testing case where concentration and hydraulic pattern on a particular tray changed completely and both had an effect on the next plate with the result that the size of the step test had to be kept low so as not to excite the non-linearities of the column. On the other hand the column could be expected to operate within the linearised envelope with a 60-second pulse width and a 20 to 25 percent pulse height.

With the smoothening of the response function transform, small scattering of the results in a small band of frequency was neglected. This resulted in the removal of small humps in the frequency response curves.

We now analyse the results obtained for each type of forcing.

REFLUX FORCING:

The frequency response characteristics of different trays seem to be in general agreement with regard to each other. The frequency response of tray 10 was restricted to lower frequencies, as only a small peak in the response (time)

was obtained for this tray. This data for this tray scattered after 0.03 radian per second frequency due to the smaller signal-to-noise ratio.

The results obtained for forcings on reflux in general agreed with those obtained by Marino et al (43). The gain curves showed a first order major lag, due to concentration lag over the particular tray but the phase lag increased for the plates farther from the top because of the series addition of lags due to liquid flow over the trays. The major time constant obtained was nearly the same for all the trays above the feed plate. This was due to the same value of vapor-liquid equilibrium constant and nearly constant liquid flow rate in this section of the column. The latter factor also contributed to the same hold up over these trays because of same weir height of all the trays. However, the major time constant for the trays below feed plate was lower due to increased equilibrium constant and higher flow rate of liquid over the trays. Tray 10 showed peculiar behavior by having two major time constants, but both smaller than of other trays. This could be attributed to the poor time response obtained for the tray.

FEED FORCING:

With forcing of the feed, the response obtained for the trays above the feed distribution plate was poorer as the tray was farther from the feed distribution plate. This was due to two factors. The forcing pulse caused only an insigni-

ficant change in the flow rate of vapors rising from the distribution plate and the composition of this vapor changed slowly. The latter was because of the composition change of this vapor depended largely on mass transfer dynamics of the tray below the feed distribution plate. Because of this only the time response of tray 6 was good enough to be reduced to the frequency domain. The frequency response of tray 6 showed significant resonance in both gain as well as phase lag. This could be due to the location of thermowells into the tray metal, so that measured temperature response of a tray was essentially the temperature of vapors entering the tray as explained in chapter IV. During a pulse on feed, the temperature of the vapors rising from the tray 7 was reduced also by the increased flow rate of cooler feed mixing on tray 7, with the result that the measured response of tray 6 was essentially due to heat transfer over the tray 7. The major time constant for the trays below the feed plate compared favourably with those obtained for these trays for forcing on the reflux.

Pulses of the square type had to be particularly avoided for this forcing because the feed tray seemed to get temporarily flooded, with the result that the effect of fluid dynamics was significant over the mass transfer dynamics.

STEAM FORCING:

With the use of the lag window function, the response

Fourier transform was quite smooth. The lag window function lowered the steady state gain, but gain in frequency band of interest had only a slight change. The effect of the lag window function on gain as well as phase lag is shown for the frequency response of tray 6 in figures 23 and 24.

All the trays showed major first order lags. The major time constant for trays above the feed tray was nearly the same, except that the tray 3 and 6 major time constants were lower by one minute. The results for these trays compared reasonably well with the forcing on the reflux. For the trays below the feed tray lower time constants were obtained but only the time constant of tray 8 was consistent with other types of forcings. The time constants for trays 9 and 10 were much lower. This could be attributed to faster temperature response of the bottom trays because of a sudden drop in the pressure at the bottom of the column at the introduction of the pulse on the steam (cutting down the steam flow). Thus the bottom tray temperature response was due to both a change (increase) in methanol concentration and a change (decrease) in the column pressure.

The trays below the feed did not show any resonance, but upper trays displayed resonance behavior in both gain as well phase lag. A similar observation was made by Powell and DeBolt(41) while pulse forcing steam to a 90-plate Deisobutanizer.

Harriot (19) analysing this behavior of distillation column, points out this is due to side capacities.

The fact for smaller phase lag for trays near the top even at higher frequencies can be explained due to quicker temperature response caused by colder reflux, as the overhead condenser handled a lower vapor load during the pulse on steam. As mentioned in chapter IV, temperature control of the reflux during the pulse test could not be achieved satisfactorily. Further for forcing on steam, the hydraulic lag was due to vapor flow rate rather than liquid flow rate, and the former being smaller did not introduce as much hydraulic phase lag for the upper trays than was introduced for bottom trays for forcings on the reflux.

The sinusoidal test results compared favourably with the pulse test. However, in the case of tray 4 the phase lag results did not agree within reasonable limits. The sinusoidal test results for tray 1 could not be obtained because of the very small amplitude of sinusoidal response.

Steam and Feed Control Valves:

The frequency response characteristics of the steam and feed control valves indicated that over the frequency of interest for the column dynamics, both valves have constant gain, but the phase lag increased due to the dead time lag of the two valves.

CONCLUSIONS:

In general the response of a plate to changes in flow rates of reflux, feed or steam could be approximated by a

major first order lag due to mass-transfer over the particular tray. The hydraulic lag, being smaller, does not exhibit itself in the gain curves up to the frequency range of interest obtained with the pulse test, but does exhibit itself in the phase lag curves. The frequency response of a tray is thus composed of major first order concentration lag (over the tray) and a series addition of the hydraulic lags up to the plate. The frequency response for the pulse forcings on the steam gave peculiar results due to pressure drop in the bottom of the column (resulting in lesser time constant for the bottom trays) and colder reflux (resulting in lesser phase lag for the upper trays). Also the pulse-test cannot be used to extract the dynamic information of trays above the feed for the forcing on the feed. However, in general, the dynamic information provided in the form of the frequency response characteristics for different forcings on the column seem to be appropriate. And because of the simpler procedure of the pulse testing method it should be extensively used to obtain dynamic behavior of complex system like distillation columns, from which simpler dynamic models could be obtained. With the recommendations mentioned in the next chapter, the method can be effectively used with less consumption of routine labor and time.

CHAPTER VII

LIMITATIONS AND RECOMMENDATIONS

In the present investigation tray temperature was used as the response function. The location of thermowells in the tray metal caused some difficulty in interpretation. As mentioned in chapter IV this measured the temperature of the vapors rising to the tray rather than temperature of the liquid on the tray. Further more this arrangement introduces a very small thermal lag depending on the tray metal. It is suggested that thermocouples be relocated so as to be submerged in the liquid on the tray.

The greatest drawback in the equipment set up was the behavior of the control valves, contrary to the ratings, namely the linear contour and reproducibility of the valves. As mentioned in chapter IV this necessitated the introduction of the random-shaped pulse, with the result that the frequency content for the same pulse width was poorer than standard pulse shapes, like displaced cosine, triangular etc. In order to force pulse on air signal to a control valve, the control valve must have a linear contour. To achieve reproducibility use of a valve positioner is recommended. With this modification a high frequency content pulse could be generated with the pulse function generator, transduced to a pneumatic signal, before forcing on the air signal to the valve. Further to obtain still higher frequency content with the same pulse

strength, the use of multicycle pulses is suggested (30).

The recording of the response on strip charts and then performing the laborious work of curve reading and punching of data on cards could be made simpler and time-saving by tape recording the input and response functions and directly feeding the taped data to the computer as proposed by Banham, Jr, (40). Banham also proposes use of dual channel filters in order to attenuate such frequencies where the existence of noise is anticipated in both the system tested and the tape-recording system.

After the introduction of 50 μ fd capacitor in type 9806-A input coupler (page 35) the dynograph temperature recording system sometimes drifted suddenly by about 2 mm, spoiling a number of pulse test recordings. This defect could not be entirely eliminated, though it did not occur too often later.

REFERENCES

1. Ceaglske, N.H., Chem. Eng. Progr. (Symposium Ser. No. 36), 57: 53 (1961).
2. Ceaglske, N.H., Ind. Eng. Chem., 48: 1002 (1956).
3. Murrill, P.W., Pike, R.W. and Smith, C.L., Chem. Eng., 75(19): 120 (Sept 9, 1968).
4. Murrill, P.W., Pike, R.W. and Smith, C.L., Chem. Eng., 75(21): 177 (Oct 7, 1968).
5. Murrill, P.W., Pike, R.W. and Smith, C.L., Chem. Eng., 75(24): 165 (Nov 18 1968).
6. Lubyen, W.L., Chem. Eng. Progr., 61(8): 74 (1965).
7. MacMullan, E.C. and Shinskey, F.G., Control Eng., p. 69 (March 1964).
8. Shinskey, F.G., ISA Journal, 10: 61 (NOV 1963).
9. Woolverton, P.F. and Murrill, P.W., Instrument Tech., p. 35 (Jan 1967).
10. Archer, D.H. and Rothfus, R.R., Chem. Eng. Progr. (Symposium Ser. No. 36), 57: 2 (1961).
11. Gould, L.A., Chem. Eng. Progr. (Symposium Ser. No. 46), 59: 155 (1963).
12. William, T.J., Chem. Eng. Progr. (Symposium Ser. No. 46), 59: 1 (1963).
13. William, T.J., Harnett, R.T. and Rose, A., Ind. Eng. Chem., 48: 1008 (1956).
14. DeBolt, R.R. and Powell, B.E., ISA Journal, 13: 43 (Sept 1966).

15. Armstrong, W.D. and Wood, R.M., Trans. Inst. Chem. Engrs. (London), 39: 65 (1961).
16. Armstrong, W.D. and Wood, R.M., Trans. Inst. Chem. Engrs. (London), 39: 80 (1961).
17. Wood, R.M. and Armstrong, W.D., Chem. Eng. Sci., 12: 272 (1960).
18. Caldwell, W.I., Coon, G.A. and Zoss, L.M., 'Frequency Response for Process Control', McGraw-Hill, 1959.
19. Harriot, P., 'Process Control', McGraw-Hill, 1964.
20. Law, V.J. and Bailey, R.V., Chem. Eng. Sci., 18: 189 (1963).
21. Nyquist, J.K., Schindler, R.N. and Gilbert, R.E., Chem. Eng. Progr. (Symposium Ser. No. 46), 59: 98 (1963).
22. Schechter, R.S. and Wissler, E.H., Ind. Eng. Chem., 51: 945 (1959).
23. Baber, M.F., Edwards, L.L., Harper, Jr., W.T., Witte, M.D. and Gerster, J.A., Chem. Eng. Progr. (Symposium Ser. No. 36), 57: 48 (1961).
24. Gilliland, E.R. and Mohr, C.M., Chem. Eng. Progr. (Symposium SER. No. 46), 59: 32 (1963).
25. Huckaba, C.E., May, F.P. and Franke, F.R., Chem. Eng. Progr. (Symposium Ser. No. 46), 59: 38 (1963).
26. Sproul, J.S. and Gerster, J.A., Chem. Eng. Progr. (Symposium Ser. No. 46), 59: 21 (1963).
27. Lees, S. and Hougen, J.O., Ind. Eng. Chem., 48: 1064 (1956).

28. Hougen, J.O., Chem. Eng. Progr. (Monograph Ser. No. 4), 60 (1964).
29. Hougen, J.O. and Walsh, R.A., Chem. Eng. Progr., 57(3): 69 (1961).
30. Clements, Jr., W.C., 'Pulse Testing for Dynamic Analysis', Ph.D. Thesis, Vanderbilt University, 1963.
31. Clements, Jr., W.C. and Schnelle, Jr., K.B., I & EC, Proc. Des. & Dev., 2(2): 94 (1963).
32. Renfroe, Jr., C.A., 'Multicomponent Distillation Dynamics', Ph.D. Thesis, Virginia Polytechnic Institute, 1965.
33. Fogle, Jr., J.B., 'Sieve Plate Distillation Dynamics', Ph.D. Thesis, Virginia Polytechnic Institute, 1966.
34. Gallier, P.W., Sliepcevich, C.M. and Puckett, T.H., Chem. Eng. Progr. (Symposium Ser. No. 36), 57: 59 (1961).
35. Homan, T.J. and Tierney, J.W., Chem. Eng. Sci., 12: 153 (1960).
36. Aseltine, J.M., 'Transform Method in Linear System Analysis', McGraw-Hill, 1958.
37. Head, F.D., Hougen, J.O. and Walsh, R.A., 'Automatic and Remote Control'— Edtrs.: Coales, J.F., Ragazzini, J.R. and Fuller, A.T., Vol. 4, p. 312, Butterworth Scientific Publications, London, England, 1961.
38. Hougen, J.O., Chem. Eng. Progr., 59(4): 49 (1963).
39. Dreifke, G.E., Hougen, J.O. and Mesmer, G., ISA Trans., 4: 353 (Oct 1962).
40. Banham, Jr., J.W., Control Eng., p. 83 (April 1965).

41. Powell, B.E. and DeBolt, R.R., 'Instrumentation in the Chemical and Petroleum Industry', Vol. 3, p. 61 (ISA Publication)— Proceedings of the Seventh National Chemical and Petroleum Instrumentation Symposium, May 23-25, 1966, at San Francisco, Calif.
42. Marino, P.A. and Stutzman, L.F., A.I.Ch.E. Journal, 12: 603 (1966).
43. Marino, P.A., Perna, A.J. and Stutzman, L.F., A.I.Ch.E., Journal, 14: 866 (1968).
44. Roberts, S.M., 'Dynamic Programming in Chemical Engineering and Process Control', Academic Press, 1964.
45. Blackman, R.B. and Tukey, J.W., 'The Measurement of Power Spectra', Dover Publications, Inc., 1958.
46. Wallaston, E.G. and Swanson, B.S., CEP Technical Manual, p. 1, Published by A.I.Ch.E., 1967.
47. Henning, T., Control Eng., p. 67 (June 1963).
48. Henning, T., Control Eng., p. 119 (Sept 1963).
49. 'Operating Manual' for Beckman Type RS Dynograph Recorder, Beckman Instruments, Inc., 1965.
50. Auns, J.: Personal communication.
51. Huang, R.C.-H.: Personal communication.
52. 'Users Manual', Published by Computing Centre, Univ. of Ottawa, Dec. 1968.

APPENDIX A

STEADY STATE OPERATING CONDITIONS OF THE COLUMN.

A.1 Flow Streams Data:

Stream	Flow Rate (usgpm)	Composition (wt.%,Methanol)	Sp.gr. (at 20°C)	Temp. (°F)
Feed	0.38	12.0	0.97	184
Reflux	0.20	99.3	0.793	96
Product	0.055	99.3	0.793	96
Bottoms	0.33	0.5	0.99	-

A.2 Temperature Profile of the Column:

Tray Number	Temperature, °F
Reflux Distribution Plate	151.5
1	154
2	159
3	164
4	172
5	183
6	192
Feed Distribution Plate	194
7	196
8	203
9	207.5
10	209

Cooling water inlet temperature:- 77 to 85 °F.

Steam pressure at Reboiler inlet:- 5 to 6 psig.

A.3 Overall Material Balance of the Column:

Stream	Stream Rate		Component Rate, lb/min	
	(gpm)	(lb/min)	Methanol	Water
Input Stream				
Feed	0.38	3.08	0.370	2.71
Output Stream				
Product	0.055	0.363	0.36	0.003
Bottoms	0.33	2.713	0.013	2.70
TOTAL	0.385	3.076	0.373	2.703

APPENDIX B

EXPERIMENTAL PULSE TEST DATA

The presented data has been read from the recorded input and output pulse curves recorded on dual-channel dynograph recorder.

In tables 2 through 9, the pulse-test data for the forcing on reflux is presented.

In tables 10 through 13, the pulse-test data for the forcing on feed is presented.

In tables 14 through 21, the pulse-test data for the forcing on steam is presented.

Included in the tables is conversion factors, to convert the data, read in mm of chart reading, into proper units.

Following nomenclature is used in the tables.

- DT1, DT2 First and second time-interval size of the input pulse data, seconds.
- DT3, DT4 First and second time-interval size of the output pulse data, seconds.
- K1, K2 Number of data points read over the time-interval DT1 and DT2 (respectively) of the input pulse curve.
- K3, K4 Number of data points read over the time-interval DT3 and DT4 (respectively) of the output pulse curve.
- TO, TM, TP are the initial, peak(max.) and final (respectively) of the output pulse curve.

TABLE 2

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 1 TO RANDOM SHAPED PULSE ON REFLUX CONTROL VALVE
 RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC
 RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 0.50 MV/CM
 CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS REFLUX FLOW RATE, PULSED AT 0.2 USGPM

FOLLOWING ARE 60 VALUES OF INPUT DATA WITH RECORDING FACTOR=495.0 MM OF CHART READING PER USGPM

0.0	1.6	4.4	4.7	6.1	11.0	11.9	13.8	17.0	18.6	20.4	20.8	21.7	22.4	23.3	24.0
29.0	33.7	34.0	34.1	34.5	34.6	34.9	35.2	35.3	35.7	35.8	35.8	35.9	36.0	36.0	36.1
36.2	36.3	36.8	37.0	37.5	37.6	37.7	37.9	38.0	38.0	38.1	38.1	38.1	38.1	38.1	38.1
38.1	38.1	38.0	35.0	32.9	26.0	21.0	19.2	12.2	11.0	10.0	0.0				

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=21, K2=40

RESPONSE IS TEMPERATURE OF TRAY 1 (FROM THE TOP), WITH FACTOR OF 42.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 124 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=11.90 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.9	2.0	2.3	2.7	3.0	3.3	3.7	4.0	4.1	4.2	4.6	4.8	5.0	5.0	5.1	5.2
5.2	5.2	5.3	5.6	5.7	5.7	5.5	5.1	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
4.8	4.7	4.4	4.2	4.1	4.0	3.9	3.9	3.8	3.8	3.7	3.5	3.4	3.4	3.5	3.4
3.2	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
2.4	2.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9	1.9	1.9	1.9
1.9	1.8	1.9	2.0	2.0	1.8	1.7	1.5	1.4	1.2	1.2	1.1	1.1	1.0	0.9	0.7
0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.3	0.2	0.2	0.1	0.0				

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=35, K4= 90

TABLE 3

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 2 TO RANDOM_SHAPED PULSE ON REFLUX CONTROL VALVE
 RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 0.50 MV/CM

CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS REFLUX FLOW RATE, PULSED AT 0.2 USGPM

FOLLOWING ARE 49 VALUES OF INPUT DATA WITH RECORDING FACTOR=495.0 MM OF CHART READING PER USGPM

0.0	2.0	7.9	11.2	12.9	15.0	16.0	21.5	22.8	23.8	26.0	33.0	35.9	36.0	36.3	36.9
37.8	38.3	38.5	39.0	39.2	39.6	39.8	39.9	40.0	40.0	40.0	40.1	40.2	40.3	40.4	40.5
40.6	40.6	40.6	40.5	40.4	37.5	34.2	34.0	26.0	24.1	22.0	20.4	15.2	13.0	9.3	5.0
0.0															

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=12, K2=38

RESPONSE IS TEMPERATURE OF TRAY 2 (FROM THE TOP), WITH FACTOR OF 42.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 144 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=11.90 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.8	1.0	1.4	2.0	2.6	2.8	3.0
3.4	3.9	4.3	5.0	5.6	5.9	6.1	6.4	6.9	7.2	7.4	8.0	8.2	8.2	8.3	8.2
8.2	8.0	8.0	8.0	8.0	7.7	7.4	7.3	7.4	7.5	7.9	7.9	7.5	7.2	7.2	7.2
7.1	7.0	6.8	6.6	6.1	6.3	6.5	6.3	6.3	6.3	6.1	6.1	6.1	6.0	6.0	6.0
6.0	6.0	5.9	5.6	5.4	5.1	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.6	4.7	4.7
4.8	4.3	4.0	4.0	4.0	4.0	3.9	3.7	3.8	3.6	3.4	3.5	3.4	3.2	3.0	3.0
3.0	2.9	2.8	2.8	2.8	2.4	2.2	2.2	2.0	2.2	2.3	2.4	2.7	2.9	2.6	2.5
2.2	2.2	2.0	1.9	1.9	2.0	1.9	1.3	1.2	1.2	1.2	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.3	0.2	0.0

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=30, K4=115

TABLE 5

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 4 TO RANDOM SHAPED PULSE ON REFLUX CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 0.50 MV/CM

CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS REFLUX FLOW RATE, PULSED AT 0.2 USGPM

FOLLOWING ARE 50 VALUES OF INPUT DATA WITH RECORDING FACTOR=495.0 MM OF CHART READING PER USGPM

0.0	5.0	10.6	11.2	15.0	19.0	20.0	22.7	24.1	25.9	28.5	31.9	31.0	31.0	31.6	31.8
32.0	32.2	32.9	33.0	33.5	33.7	34.2	34.3	34.7	35.0	35.9	36.0	36.4	36.9	37.0	37.1
37.1	37.1	37.1	37.1	35.0	32.0	30.0	18.3	15.7	12.0	8.0	6.3	3.7	3.4	3.0	2.3
1.0	0.0														

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=10, K2=41

RESPONSE IS TEMPERATURE OF TRAY 4 (FROM THE TOP), WITH FACTOR OF 40.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 149 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=12.50 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.6	0.7	1.2	1.3	2.0	2.4	2.8	3.1	4.0
4.9	5.0	6.0	7.5	9.1	10.0	11.6	12.4	13.1	14.1	15.0	15.4	15.6	16.0	16.2	16.8
17.1	17.3	18.1	18.2	18.1	18.0	17.8	18.0	18.0	18.0	18.0	17.5	17.3	17.9	18.0	18.0
18.0	17.8	17.8	17.1	17.1	17.0	16.8	16.7	16.5	16.0	16.0	15.8	15.0	14.3	14.3	14.0
13.0	13.0	13.0	13.0	12.9	12.8	12.6	12.2	12.0	12.0	11.4	11.2	11.2	11.2	11.2	11.0
10.3	9.8	9.2	8.4	8.1	8.1	8.0	7.8	7.5	7.5	7.5	7.5	7.0	6.7	6.0	6.0
5.8	5.8	5.9	5.8	5.7	5.4	4.3	5.2	5.1	5.3	5.3	5.3	5.2	5.1	5.4	5.9
6.1	6.3	6.3	6.1	6.0	6.0	6.0	6.0	6.0	6.0	5.0	5.0	5.0	4.4	4.0	4.2
4.2	3.0	2.9	2.7	2.0	2.0	2.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	0.8	0.0											

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=50, K4=100

TABLE 6

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 6 TO RANDOM SHAPED PULSE ON REFLUX CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED=1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) =0.50 MV/CM

CHANNEL 2 (OUTPUT) =0.02 MV/CM

INPUT IS REFLUX FLOW RATE, PULSED AT 0.2 USGPM

FOLLOWING ARE 82 VALUES OF INPUT DATA WITH RECORDING FACTOR=495.0 MM OF CHART READING PER USGPM

0.0	5.0	9.0	9.7	11.8	14.0	17.0	17.2	20.7	22.8	31.2	31.8	33.0	33.5	34.9	35.4
36.5	37.4	37.7	37.9	38.0	38.3	38.3	38.4	38.5	38.6	38.7	38.8	38.9	39.0	39.0	39.1
39.1	39.2	39.2	39.3	39.3	39.3	39.4	39.4	39.5	39.5	39.6	39.6	39.6	38.8	37.4	32.0
22.3	22.2	21.6	21.2	20.6	20.3	20.0	19.9	19.0	16.3	16.0	15.9	15.7	15.3	12.2	11.9
11.8	11.7	11.6	11.4	9.0	5.0	5.0	3.0	2.4	2.3	2.3	2.3	2.3	2.2	2.1	2.1
2.0	0.0														

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=12, K2=71

RESPONSE IS TEMPERATURE OF TRAY 6 (FROM THE TOP), WITH FACTOR OF 38.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 113 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=13.16 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.5	1.0	1.4
1.8	2.4	3.5	4.7	5.4	6.3	7.6	8.9	9.8	11.0	12.0	13.2	14.9	16.2	17.7	18.9	
20.0	21.5	22.4	23.1	24.2	25.3	26.4	27.0	27.9	28.5	29.3	29.8	30.1	30.3	30.7	30.9	
31.1	31.2	31.0	30.4	29.8	29.2	28.1	27.0	26.0	24.9	23.4	22.4	21.9	21.0	20.0	19.3	
19.0	18.7	18.8	18.8	19.0	19.0	18.1	18.2	18.2	17.9	17.9	17.3	17.5	17.2	17.0	16.9	
15.1	14.1	13.5	13.5	13.2	12.5	12.8	12.4	12.8	12.3	12.0	11.8	11.2	10.9	10.0	9.2	
8.8	8.0	7.0	6.6	6.6	6.0	5.0	4.9	4.9	4.8	4.0	3.3	2.7	2.2	1.2	0.9	
0.0																

INTERVAL WIDTHS ARE DT3=5.0, DT4=20.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=50, K4= 64

TABLE 7

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 8 TO RANDOM_SHAPED PULSE ON REFLUX CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 0.50 MV/CM

CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS REFLUX FLOW RATE, PULSED AT 0.2 USGPM

FOLLOWING ARE 52 VALUES OF INPUT DATA WITH RECORDING FACTOR=495.0 MM OF CHART READING PER USGPM

0.0	5.6	10.7	11.0	12.0	15.0	18.2	20.8	21.4	24.0	26.3	31.9	32.1	32.5	33.6	34.0
34.2	34.4	34.5	34.8	35.0	35.0	35.0	35.0	35.1	35.6	35.8	35.8	35.9	36.0	36.1	36.1
36.0	36.0	35.9	33.5	32.4	22.0	21.0	18.9	18.0	12.5	12.1	11.3	10.1	9.6	2.0	1.2
1.0	0.6	0.3	0.0												

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=10, K2=43

RESPONSE IS TEMPERATURE OF TRAY 8 (FROM THE TOP), WITH FACTOR OF 39.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 113 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=12.82 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.2	1.6
2.5	2.9	2.5	3.0	3.3	3.8	4.2	4.7	5.0	6.0	6.4	6.9	7.3	8.7	9.5	10.1	
10.3	11.1	12.3	12.8	12.7	12.7	12.8	12.9	12.9	13.0	13.1	13.1	13.1	13.0	12.6	12.4	
12.2	12.1	12.0	12.0	12.6	13.0	13.0	13.0	13.0	12.9	12.6	12.2	12.0	12.0	11.9	11.5	
11.5	11.6	11.7	11.4	11.0	11.0	10.3	10.0	9.8	9.6	9.4	9.2	9.0	8.2	8.0	7.9	
7.4	7.1	7.0	7.0	6.4	5.6	5.0	4.0	4.0	4.0	3.8	3.0	3.0	3.0	3.0	3.0	
2.7	2.6	2.5	2.3	2.3	2.0	2.0	1.9	1.9	2.0	2.0	1.5	1.4	1.2	1.2	1.2	0.2
0.0																

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=70, K4= 44

TABLE 8

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 9 TO RANDOM SHAPED PULSE ON REFLUX CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 0.50 MV/CM

CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS REFLUX FLOW RATE, PULSED AT 0.2 USGPM

FOLLOWING ARE 45 VALUES OF INPUT DATA WITH RECORDING FACTOR=495.0 MM OF CHART READING PER USGPM

0.0	2.0	11.5	11.8	14.1	16.7	18.5	26.5	27.2	27.6	32.0	32.3	32.8	33.0	33.3	33.7
34.0	34.9	35.0	35.2	35.5	35.9	36.1	36.2	36.4	36.7	36.8	37.0	37.2	37.5	37.6	37.7
37.8	37.9	37.9	38.0	38.0	38.0	38.0	37.0	32.0	19.5	14.5	11.0	0.0			

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=11, K2=35

RESPONSE IS TEMPERATURE OF TRAY 9 (FROM THE TOP), WITH FACTOR OF 39.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 95 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=12.82 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.5
0.6	0.9	1.0	1.0	1.0	1.1	1.5	1.9	1.9	2.1	2.5	3.0	3.4	3.9	4.2	4.9	
5.3	5.7	6.0	6.0	6.0	6.0	6.0	6.2	6.2	6.0	6.0	6.0	6.0	6.0	5.9	5.8	5.8
6.0	6.0	5.9	5.9	5.3	5.0	5.0	5.0	5.0	4.9	4.5	4.0	3.7	3.5	3.1	3.0	
3.0	3.0	3.0	2.7	2.6	2.5	2.4	2.0	2.0	2.0	1.8	1.8	1.7	1.9	2.0	1.9	
1.5	1.1	0.5	0.3	0.0												

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=50, K4=36

TABLE 9

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 10 TO RANDOM SHAPED PULSE ON REFLUX CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 0.50 MV/CM

CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS REFLUX FLOW RATE, PULSED AT 0.2 USGPM

FOLLOWING ARE 52 VALUES OF INPUT DATA WITH RECORDING FACTOR=495.0 MM OF CHART READING PER USGPM

0.0	1.0	10.2	12.0	18.0	22.0	26.4	27.0	34.0	34.7	35.2	35.9	36.4	37.3	37.5	37.8
37.9	38.0	38.1	38.4	38.8	38.9	38.9	39.0	39.1	39.3	39.4	39.6	39.6	39.7	39.8	40.1
40.3	40.4	40.5	40.6	40.5	40.5	38.5	36.2	23.5	22.0	18.0	10.6	10.4	9.9	2.0	1.1
1.0	0.8	0.6	0.0												

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=11, K2=42

RESPONSE IS TEMPERATURE OF TRAY 10 (FROM THE TOP), WITH FACTOR OF 39.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 86 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=12.82 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.2	0.6	0.9	1.0	1.0	1.0	1.3	1.8	2.0	2.2	2.6	2.6	2.6
2.7	2.7	3.0	3.0	3.1	3.2	3.3	3.3	3.4	3.5	3.1	3.1	3.1	3.1	3.2	3.2
3.2	3.1	3.1	3.1	3.1	3.0	3.0	3.0	2.7	2.5	2.5	2.1	2.1	2.0	2.0	2.0
2.0	2.2	2.3	2.3	2.3	2.3	2.2	2.1	2.0	2.0	1.9	1.8	1.8	1.2	1.3	1.3
1.0	1.0	0.8	0.5	0.2	0.0										

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=80, K4= 7

TABLE 10

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 6 TO RANDOM SHAPED PULSE ON FEED CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 0.50 MV/CM

CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS FEED FLOW RATE, PULSED AT 0.38 USGPM

FOLLOWING ARE 58 VALUES OF INPUT DATA WITH RECORDING FACTOR=380.0 MM OF CHART READING PER USGPM

0.0	0.2	0.6	3.0	9.2	10.7	13.0	15.2	20.0	22.4	23.3	23.7	25.0	25.0	25.5	25.9
25.9	25.9	26.1	26.2	26.2	26.2	26.2	26.4	26.8	26.8	26.8	26.8	26.8	26.8	26.8	26.9
26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9
4.0	3.5	3.5	3.3	3.3	3.0	3.0	2.0	0.5	0.0						

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE KI=16, K2=43

RESPONSE IS TEMPERATURE OF TRAY 6 (FROM THE TOP), WITH FACTOR OF 38.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 91 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=13.16 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.5	0.7	0.8	0.9	1.0	1.1
1.3	1.7	2.0	2.1	3.0	3.8	4.0	4.5	4.9	5.3	5.8	5.8	6.1	6.3	6.7	7.0	7.1
7.2	7.2	7.2	7.2	7.2	7.0	6.8	6.7	6.5	6.3	6.2	6.2	6.0	6.0	6.0	6.2	6.2
6.1	6.0	6.0	5.7	5.6	5.3	5.2	5.1	5.0	4.9	4.9	4.9	4.8	4.9	5.0	5.2	5.4
5.3	5.2	5.0	4.4	4.3	4.1	4.0	3.9	3.8	3.6	3.4	3.4	3.3	3.2	3.0	2.6	2.3
2.0	1.5	1.1	0.9	0.8	0.8	0.7	0.7	0.5	0.3	0.0						

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=20, K4= 72

TABLE 11

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 8 TO RANDOM SHAPED PULSE ON FEED CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 0.50 MV/CM

CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS FEED FLOW RATE, PULSED AT 0.38 USGPM

FOLLOWING ARE 62 VALUES OF INPUT DATA WITH RECORDING FACTOR=380.0 MM OF CHART READING PER USGPM

0.0	1.3	2.1	2.3	3.0	7.7	12.0	14.0	16.2	20.5	22.2	25.0	28.3	30.0	31.3	32.3
33.1	33.7	34.0	34.0	34.0	34.1	34.1	34.1	34.2	34.2	34.1	34.1	34.1	34.1	34.1	34.2
34.2	34.2	34.1	34.1	34.1	34.0	32.0	24.0	14.0	8.3	7.0	5.2	5.2	5.0	5.0	4.8
4.7	3.2	2.0	1.8	1.5	1.3	1.3	1.1	1.1	1.0	0.8	0.6	0.3	0.0	0.0	0.0

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=11, K2=52

RESPONSE IS TEMPERATURE OF TRAY 8 (FROM THE TOP), WITH FACTOR OF 39.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 84 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=12.82 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.8	1.2	1.8	2.7	3.4	4.1	5.2
5.8	6.6	7.5	8.2	8.7	9.3	10.1	10.3	10.4	11.1	11.3	11.5	11.1	11.1	11.0	11.7
12.1	11.8	11.2	10.5	10.1	10.1	9.1	9.0	9.0	8.9	8.8	7.8	7.6	7.4	7.0	7.0
6.9	6.3	6.0	5.7	4.8	4.8	4.6	4.8	4.3	4.0	4.0	3.3	3.0	2.9	3.4	3.5
3.2	3.0	2.4	2.0	2.0	1.2	1.1	1.0	1.1	1.1	1.0	1.0	0.9	0.8	0.7	0.7
0.7	0.6	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=25, K4= 60

TABLE 12

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 9 TO RANDOM SHAPED PULSE ON FEED CONTROL VALVE
 RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC
 RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 0.50 MV/CM
 CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS FEED FLOW RATE, PULSED AT 0.38 USGPM

FOLLOWING ARE 78 VALUES OF INPUT DATA WITH RECORDING FACTOR=380.0 MM OF CHART READING PER USGPM

0.0	1.8	2.2	3.6	4.8	10.0	13.5	14.6	17.7	20.0	22.7	23.6	25.4	26.4	28.1	28.4
28.6	29.0	29.3	29.3	29.7	29.8	29.9	30.0	30.0	30.0	30.1	30.2	30.2	30.3	30.4	30.6
30.8	30.8	30.8	30.8	29.9	27.5	23.9	20.7	16.7	15.2	11.2	10.5	10.0	9.0	7.7	7.0
4.0	2.3	2.3	2.0	2.0	2.0	2.0	1.9	1.9	1.8	1.4	1.3	1.2	1.0	0.9	0.9
0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.7	0.6	0.4	0.2	0.0	0.0	0.0

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=16, K2=63

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RESPONSE IS TEMPERATURE OF TRAY 9 (FROM THE TOP), WITH FACTOR OF 39.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 104 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=12.82 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.5	6.5	7.3	8.0	9.0	9.8	10.0	10.1	10.1	10.2	10.2	10.0	9.8	8.7	8.3	8.2
8.0	8.0	8.0	7.5	7.0	7.0	7.0	6.9	6.7	5.9	5.8	5.5	5.0	5.0	5.0	5.0
5.0	5.0	5.0	4.1	3.6	3.3	3.0	3.0	3.0	3.0	3.0	2.9	2.8	2.9	2.8	2.6
2.5	2.8	2.8	3.0	3.0	3.0	2.5	2.3	2.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0
2.0	2.0	2.0	2.0	2.0	1.9	1.8	2.0	2.0	1.7	1.5	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.2	1.0	1.0	1.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=20, K4= 85

TABLE 13

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 10 TO RANDOM SHAPED PULSE ON FEED CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) =0.50 MV/CM

CHANNEL 2 (OUTPUT) =0.02 MV/CM

INPUT IS FEED FLOW RATE, PULSED AT 0.38 USGPM

FOLLOWING ARE 73 VALUES OF INPUT DATA WITH RECORDING FACTOR=380.0 MM OF CHART READING PER USGPM

0.0	1.5	2.0	3.8	8.7	12.5	13.2	14.0	18.0	21.8	22.9	25.0	26.2	28.3	29.6	29.7
29.8	31.3	31.7	31.6	31.3	31.3	31.2	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
31.0	31.0	31.0	30.1	28.9	26.9	21.4	18.4	14.7	11.5	8.0	5.6	4.8	3.7	3.5	3.3
3.3	3.0	3.0	2.7	2.5	2.3	2.0	2.0	2.0	1.9	1.9	1.9	1.9	1.9	1.9	1.0
1.0	1.0	1.0	0.8	0.8	0.8	0.8	0.4	0.0							

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=21, K2=53

RESPONSE IS TEMPERATURE OF TRAY 10 (FROM THE TOP), WITH FACTOR OF 39.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 83 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=12.82 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.2	1.6	1.9	2.0	2.8	3.1	3.0	3.2	3.5	3.5	3.7	4.0	4.0	4.0	4.0	4.0
4.8	4.3	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.8	3.7	3.5	3.3
3.0	3.0	3.0	2.9	2.7	2.5	2.3	2.3	2.0	1.8	1.6	1.7	1.8	1.6	1.6	1.2
1.3	1.4	1.3	1.3	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0.8	0.3	0.0													

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=25, K4= 59

TABLE 14

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 1 TO RANDOM SHAPED PULSE ON STEAM CONTROL VALVE
 RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC
 RECORDING SENSITIVITY, CHANNEL 1 (INPUT) =5.00 MV/CM
 CHANNEL 2 (OUTPUT)=0.02 MV/CM

INPUT IS STEAM CONTROL VALVE STEM POSITION

FOLLOWING ARE 48 VALUES OF INPUT DATA WITH RECORDING FACTOR=192.0 MM OF CHART READING PER INCH

0.0	1.0	4.0	5.8	8.3	10.0	12.4	15.5	18.1	21.3	23.0	25.0	25.3	25.3	25.3	25.2
25.2	25.2	25.2	25.5	25.5	25.2	25.3	25.3	25.4	25.4	25.3	25.3	25.4	25.3	25.3	25.3
25.5	25.5	25.3	25.2	25.2	23.4	20.0	16.7	13.0	11.0	9.1	7.0	4.2	3.0	1.0	0.0

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1= 6, K2=43

RESPONSE IS TEMPERATURE OF TRAY 1 (FROM THE TOP), WITH FACTOR OF 42.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 128 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=11.90 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.4	0.6	0.9	1.1	1.3	1.7	1.9	2.0	2.3
2.7	3.0	3.1	3.5	4.1	4.4	4.3	4.3	4.2	4.3	4.3	4.2	4.1	4.0	4.0	4.0
4.0	3.9	3.8	3.8	3.7	3.6	3.5	3.5	3.4	3.3	3.4	3.6	3.6	3.3	3.2	3.1
3.1	3.0	3.1	3.0	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
3.0	3.0	2.9	2.7	2.3	2.3	2.2	2.2	2.2	2.2	2.2	2.3	2.5	2.6	2.3	2.4
2.3	2.2	2.2	2.0	2.0	2.0	2.0	2.1	2.0	2.0	2.0	2.0	2.1	2.0	2.0	1.9
1.0	1.8	1.4	1.3	1.1	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	1.0
1.0	0.9	0.9	0.7	0.7	0.8	0.8	0.6	0.5	0.3	0.2	0.1	0.2	0.1	0.1	0.0

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=20, K4=109

RESPONSE PULSE CURVE TO= 25.0, TM=1175.0 AND TP= 115.0

TABLE 15

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 2 TO RANDOM SHAPED PULSE ON STEAM CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 5.00 MV/CM

CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS STEAM CONTROL VALVE STEM POSITION

FOLLOWING ARE 44 VALUES OF INPUT DATA WITH RECORDING FACTOR=192.0 MM OF CHART READING PER INCH

0.0	2.0	4.4	6.0	7.7	9.4	11.0	14.0	16.3	19.7	20.0	22.0	24.0	25.1	25.9	25.8
25.8	25.8	25.7	25.8	25.9	25.9	25.9	25.9	25.9	25.9	25.9	25.8	25.8	25.8	25.8	25.2
24.8	23.3	23.3	21.3	19.2	17.2	15.1	12.5	9.4	6.2	2.3	0.0				

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=11, K2=34

RESPONSE IS TEMPERATURE OF TRAY 2 (FPCM THE TOP), WITH FACTOR OF 42.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 121 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=11.90 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.8	1.4	1.8	2.3	2.5	3.0	3.4	3.8	4.0
4.3	4.9	5.2	5.9	6.0	6.2	6.3	6.3	6.2	6.2	6.3	6.1	5.8	5.7	5.4	5.1	5.0
4.9	4.9	4.7	4.9	4.9	4.7	4.4	4.4	4.1	4.1	4.0	4.0	3.6	3.4	3.5	3.9	3.9
3.8	3.9	3.3	3.3	3.3	3.2	3.1	3.3	3.3	3.3	3.4	3.4	3.9	3.4	3.4	3.1	3.0
3.1	3.1	3.1	3.1	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.9	2.8	2.6
2.4	2.4	2.5	2.7	2.8	2.8	2.9	2.9	2.6	2.4	2.2	2.2	2.3	2.5	2.8	2.8	2.8
2.8	2.7	2.2	2.0	2.0	2.0	2.0	2.0	1.8	1.5	1.3	1.3	1.4	1.5	1.6	1.5	1.1
1.0	1.0	0.8	0.8	0.9	0.7	0.3	0.3	0.2	0.0							

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=25, K4= 97

RESPONSE PULSE CURVE TO= 25.0, TM=1000.0 AND TP= 110.0

TABLE 16

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 3 TO RANDOM SHAPED PULSE ON STEAM CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC
 RECORDING SENSITIVITY, CHANNEL 1 (INPUT) =5.00 MV/CM
 CHANNEL 2 (OUTPUT) =0.02 MV/CM

INPUT IS STEAM CONTROL VALVE STEM POSITION

FOLLOWING ARE 39 VALUES OF INPUT DATA WITH RECORDING FACTOR=192.0 MM OF CHART READING PER INCH

0.0	0.7	2.2	3.0	4.8	6.0	7.3	9.9	12.8	16.0	18.6	20.1	21.8	24.2	25.6	25.7
25.7	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.9	24.0
20.5	15.8	12.6	8.0	6.7	2.0	0.0									

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE KI= 7, K2=33

RESPONSE IS TEMPERATURE OF TRAY 3 (FROM THE TOP), WITH FACTOR OF 42.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 106 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=11.90 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.4	2.1	2.9	3.2	3.8	4.1	4.8	5.0
5.8	6.6	7.2	7.7	7.9	8.0	8.0	8.1	8.0	7.9	7.9	8.0	7.7	7.4	7.4	7.3
7.0	7.0	7.0	7.0	7.0	6.7	6.5	6.5	6.4	6.2	6.2	6.1	6.1	5.9	5.7	5.4
5.2	5.0	5.0	5.0	4.9	4.9	4.8	4.9	4.9	4.8	4.0	4.0	4.0	3.8	3.6	3.2
3.0	3.0	3.3	3.7	3.5	3.2	3.3	3.3	3.2	3.2	3.3	3.7	3.5	3.2	2.9	2.8
2.6	2.5	2.5	2.2	2.1	2.0	2.0	1.9	1.8	1.8	1.3	1.0	0.8	0.8	0.8	0.8
0.8	0.8	0.4	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.0					

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=20, K4= 87

RESPONSE PULSE CURVE TC= 25.0, TM= 955.0 AND TP= 135.0

TABLE 17

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 4 TO RANDOM SHAPED PULSE ON STEAM CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 5.00 MV/CM

CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS STEAM CONTROL VALVE STEP POSITION

FOLLOWS ARE 51 VALUES OF INPUT DATA WITH RECORDING FACTOR=102.0 MM OF CHART READING PER INCH

0.0	1.3	3.4	6.2	9.2	11.3	14.1	18.1	22.0	25.0	27.7	29.8	30.0	30.0	30.0	30.0
30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	29.9	29.9	29.7	28.6	28.0	24.5	22.6	20.0
17.7	16.8	15.6	14.3	13.0	11.4	9.9	8.4	7.4	6.8	6.5	6.1	5.3	4.0	3.0	2.2
1.3	0.2	0.0													

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1= 7, K2=45

RESPONSE IS TEMPERATURE OF TRAY 4 (FROM THE TOP), WITH FACTOR OF 40.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWS ARE 131 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=12.50 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.3	1.3	2.6	3.8	5.0	6.1	6.3	8.7	9.3	10.1	11.0
11.4	11.5	11.2	11.1	11.1	11.0	11.0	11.0	11.0	11.0	11.2	11.2	11.2	11.0	11.0	11.0
10.0	10.0	9.8	9.7	9.7	9.8	10.0	10.0	10.0	9.4	9.2	9.4	9.8	9.2	9.6	9.0
9.4	9.7	9.0	9.0	9.0	8.7	8.7	8.9	8.3	8.1	8.0	8.0	8.0	8.0	8.3	8.4
7.4	7.5	7.7	7.7	7.0	7.0	7.0	7.0	7.0	7.0	6.8	6.8	6.8	6.5	6.3	6.0
5.0	5.0	4.6	4.7	5.0	4.8	4.0	3.8	4.0	4.2	4.2	3.8	3.7	3.6	3.3	3.2
3.7	3.0	3.2	3.0	3.0	3.0	2.8	2.7	2.7	3.0	3.2	3.0	2.7	2.0	2.0	1.8
1.8	1.9	1.8	1.8	2.0	5.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5
1.0	0.7	0.0													

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=20, K4=112

RESPONSE PULSE CURVE TD= 20.0, TM=1205.0 AND TP= 85.0

TABLE 19

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 8 TO RANDOM SHAPED PULSE ON STEAM CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC

RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 5.00 MV/CM

CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS STEAM CONTROL VALVE STEM POSITION

FOLLOWING ARE 47 VALUES OF INPUT DATA WITH RECORDING FACTOR=192.0 MM OF CHART READING PER INCH

0.0	1.0	1.5	2.0	3.2	3.3	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.2	12.2	13.1
13.8	15.3	16.1	17.0	18.7	19.5	20.3	22.2	23.0	23.4	23.2	22.6	21.7	21.5	19.5	18.0
17.1	16.0	14.0	12.8	11.2	10.2	9.4	8.3	7.0	6.9	5.0	4.9	2.2	2.6	0.0	

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1= 6, K2=42

RESPONSE IS TEMPERATURE OF TRAY 8 (FROM THE TOP), WITH FACTOR OF 39.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 106 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=12.82 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.2	1.5	2.1
3.0	4.0	5.0	5.5	5.7	5.7	6.0	6.1	6.1	6.5	6.9	7.0	7.0	7.2	7.6	7.2	7.0
7.0	7.0	7.0	7.0	7.0	7.0	6.9	6.6	6.3	6.7	6.6	6.1	6.2	6.2	6.7	6.6	6.7
6.7	6.9	6.3	6.0	5.6	5.0	5.1	5.0	4.9	4.8	5.0	5.0	5.1	4.8	4.7	4.7	4.6
5.0	4.8	4.0	4.0	3.5	3.7	3.5	4.0	3.7	4.0	3.6	3.1	3.4	3.2	3.3	3.3	3.0
2.9	2.6	2.8	2.4	2.9	2.0	2.8	2.2	2.2	2.0	2.0	1.4	1.2	1.2	1.2	1.2	1.0
1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.5	0.5	0.0							

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=30, K4= 77

RESPONSE PULSE CURVE T0= 55.0, TM= 905.0 AND TP= 155.0

TABLE 20

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 9 TO RANDOM SHAPED PULSE ON STEAM CONTROL VALVE

RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC
 RECORDING SENSITIVITY, CHANNEL 1 (INPUT) = 5.00 MV/CM
 CHANNEL 2 (OUTPUT) = 0.02 MV/CM

INPUT IS STEAM CONTROL VALVE STEM POSITION

FOLLOWING ARE 46 VALUES OF INPUT DATA WITH RECORDING FACTOR=192.0 MM OF CHART READING PER INCH

0.0	0.7	2.5	4.0	5.7	7.2	9.2	11.0	13.2	15.0	17.8	19.7	23.5	29.0	30.0	30.0
30.2	30.2	30.2	30.2	30.3	30.2	30.2	30.3	30.8	30.8	30.8	30.8	30.8	30.8	30.7	30.7
30.7	30.7	30.0	30.0	28.0	25.0	20.0	18.0	15.5	12.6	8.6	4.7	1.0	0.0		

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1=10, K2=37

RESPONSE IS TEMPERATURE OF TRAY 9 (FROM THE TOP), WITH FACTOR OF 39.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 54 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=12.82 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.0	0.4	0.9	1.5	2.0	2.6	3.0	3.2	4.2	5.0	5.8
6.3	7.0	8.0	8.8	9.0	9.0	8.8	8.3	8.0	8.2	8.7	8.7	8.4	7.9	7.8
7.1	6.6	6.0	5.8	5.7	5.8	5.4	4.8	4.0	4.0	3.4	3.1	3.0	3.1	2.4
2.0	1.9	1.2	0.9	0.6	0.0									

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=25, K4= 30

RESPONSE PULSE CURVE TO= 25.0, TM= 410.0 AND TP= 100.0

TABLE 21

EXPERIMENTAL PULSE TEST DATA FOR RESPONSE OF TRAY 10 TO RANDOM-SHAPED PULSE ON STEAM CONTROL VALVE
 RECORDING CHANNEL DATA IS:

CHART SPEED= 1 MM/SEC
 RECORDING SENSITIVITY, CHANNEL 1 (INPUT) =5.00 MV/CM
 CHANNEL 2 (OUTPUT)=0.02 MV/CM

INPUT IS STEAM CONTROL VALVE STEM POSITION

FOLLOWING ARE 40 VALUES OF INPUT DATA WITH RECORDING FACTOR=192.0 MM OF CHART READING PER INCH

0.0	2.7	6.0	8.8	11.2	15.7	19.3	22.3	25.8	29.0	28.1	28.3	28.2	28.2	28.2	28.1
29.1	28.1	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	26.3	23.0	19.4	15.8
13.0	12.2	8.7	6.0	2.8	0.8	0.3	0.0								

INTERVAL WIDTHS ARE DT1=2.0, DT2=2.5 AND DATA POINTS READ OVER THE INTERVAL ARE K1= 8, K2=33

RESPONSE IS TEMPERATURE OF TRAY 10 (FROM THE TOP), WITH FACTOR OF 39.0 F/MV AT THE TRAY TEMPERATURE

FOLLOWING ARE 45 VALUES OF OUTPUT DATA WITH RECORDING FACTOR=12.82 MM OF CHART READING PER F

0.0	0.0	0.0	0.0	0.2	0.8	1.0	1.7	1.9	2.1	2.7	2.9	3.0	3.2	3.7	4.0
4.2	3.8	3.0	2.9	2.3	1.9	1.8	1.8	2.0	2.7	2.9	2.7	2.3	1.5	1.6	1.6
2.0	1.3	1.2	1.3	1.2	1.0	1.0	1.0	1.0	1.0	0.9	0.3	0.0			

INTERVAL WIDTHS ARE DT3=5.0, DT4=10.0 AND DATA POINTS READ OVER THE INTERVAL ARE K3=20, K4= 26.

RESPONSE PULSE CURVE TO= 15.0, TM= 345.0 AND TP= 80.0

APPENDIX C

C.1 NUMERICAL EVALUATION OF THE PULSE:

To numerically evaluate A, B, C and D of equations (3.3.2) through (3.3.5) from the experimental data, trapezoidal rule,

$$\int_b^a f(t) dt = \Delta t \left\{ \frac{f_0}{2} + f_1 + f_2 + \dots + f_{n-1} + \frac{f_n}{2} \right\} \dots\dots (C.1.1)$$

has been used. This transforms equations (3.3.2) through (3.3.5) to the following form.

$$A = \Delta t_y \sum_{k=1}^{n-1} y(k \Delta t_y) \cos(\omega k \Delta t_y) \dots\dots (C.1.2)$$

$$B = \Delta t_y \sum_{k=1}^{n-1} y(k \Delta t_y) \sin(\omega k \Delta t_y) \dots\dots (C.1.3)$$

$$C = \Delta t_x \sum_{l=1}^{m-1} x(l \Delta t_x) \cos(\omega l \Delta t_x) \dots\dots (C.1.4)$$

$$D = \Delta t_x \sum_{l=1}^{m-1} x(l \Delta t_x) \sin(\omega l \Delta t_x) \dots\dots (C.1.5)$$

where (excluding zero end points), n-1 points are read on y(t) curve at intervals of Δt_y and m-1 points are read on x(t) curve at intervals of Δt_x . With the chosen value of in equations (C.1.2) through (C.1.5) and performing the indicated summations using experimental data for x(t) and y(t) will yield A, B, C and D. From these M.R., ϕ and $s(\omega)_n$ can be calculated as per equations (3.3.6) through (3.3.10).

The trapezoidal rule is strictly true when the integral function can be divided in straight segments. In above equations trapezoidal rule is applied to input/output pulse functions multiplied with sine or cosine functions. At higher values of ω , the integrand function seems no longer possess straight line segments over chosen time intervals, as the function starts oscillating faster and faster with increasing value of ω . Thus the approximation of product curves, no matter which quadrature formula is used, rapidly deteriorates, so that with a given accuracy in $x(t)$ and $y(t)$ a value of frequency will eventually be reached where quadrature formula becomes completely useless.

One modified quadrature formula is to write equation (3.3.1) in the following form.

$$G(j\omega) = \frac{\Delta t_y \left[\frac{\sin(\omega \Delta t_y / 2)}{(\omega \Delta t_y / 2)} \right] \sum_{k=1}^n y(k \Delta t_y) e^{-j \omega k \Delta t_y}}{\Delta t_x \left[\frac{\sin(\omega \Delta t_x / 2)}{(\omega \Delta t_x / 2)} \right] \sum_{l=1}^m x(l \Delta t_x) e^{-j \omega l \Delta t_x}} \dots\dots\dots (C.1.6)$$

A second widely used method of numerical calculations for these transforms is approximation of the pulse curve by the tops of number of trapezoids of equal width. This trapezoidal approximation can also be applied to entire fourier transform, giving

$$G(j\omega) = \frac{\Delta t_y \left[\frac{\sin(\omega \Delta t_y / 2)}{(\omega \Delta t_y / 2)} \right] \sum_{k=1}^{2n} y(k \Delta t_y) e^{-j \omega k \Delta t_y}}{\Delta t_x \left[\frac{\sin(\omega \Delta t_x / 2)}{(\omega \Delta t_x / 2)} \right] \sum_{l=1}^{2m} x(l \Delta t_x) e^{-j \omega l \Delta t_x}} \dots\dots\dots (C.1.7)$$

Hougen and Walsh (29) point out that equation (C.1.7) gives the exact Fourier transform when applied to a pulse composed of straight line segments, if the segment boundaries coincide with Δt -boundaries.

C.2 COMPUTER PROGRAM FOR REDUCTION OF EXPERIMENTAL PULSE-TEST DATA INTO FREQUENCY RESPONSE DATA (WITH SAMPLE COMPUTED RESULTS):

The computer program, written in Fortran IV language, is presented on pages 110 through 122. Comment cards have been invariably placed in the deck to display sequence of computations. A sample of computed results, giving frequency response of tray 6 for the forcing on the steam is presented on pages 123 and 124.

C

FREQUENCY RESPONSE EVALUATION FROM EXPERIMENTAL PULSE-TEST DATA

FOLLOWING IS NOTATION OF MAIN SYMBOLS USED IN THE PROGRAM

X(I)

INPUT PULSE DATA, MM OF CHART READING

Y(I)

OUTPUT PULSE DATA, MM OF CHART READING

T

TIME FROM INTRODUCTION OF PULSE, SECONDS

W(I)

FREQUENCY, RADIAN/SECOND

DAR(I)

DYNAMIC AMPLITUDE RATIO OR GAIN, F/GPM OR F/INCH

DARN(I)

NORMALISED GAIN

PHASE(I)

PHASE LAG, DEGREES

SWN(I)

NORMALISED FREQUENCY CONTENT

SN

AREA UNDER INPUT PULSE CURVE, (MM OF CHART READING)*SECONDS

RE

REAL PART OF COMPLEX NUMBER

XIM

IMAGINARY PART OF COMPLEX NUMBER

XMR

MAGNITUDE OF COMPLEX NUMBER

ANGLF

ANGLE OF COMPLEX NUMBER

FORMR(I)

MAGNITUDE OF FOURIER TRANSFORM OF INPUT PULSE CURVE, GPM*SEC OR INCH*SEC

FORANG(I)

ANGLE OF FOURIER TRANSFORM OF INPUT PULSE CURVE, DEGREES

RESMR(I)

MAGNITUDE OF FOURIER TRANSFORM OF OUTPUT PULSE CURVE, F*SEC

RESANG(I)

ANGLE OF FOURIER TRANSFORM OF OUTPUT PULSE CURVE, DEGREES

0001

1110

DIMENSION X(100), Y(500), W(100), DAR(100), DARN(100), PHASE(100),
1SWN(100), YY(500), YYY(500), DARN(100), PHASER(100), YC(500), FORMR(100),
2), FORANG(100), RESMR(100), RESANG(100)

READING IN OF THE EXPERIMENTAL DATA

DT1, DT2 ARE FIRST AND SECOND TIME-INTERVAL SIZE OF INPUT PULSE CURVE, SEC.
DT3, DT4 ARE FIRST AND SECOND TIME-INTERVAL SIZE OF OUTPUT PULSE CURVE, SEC.
WMAX IS MAXIMUM FREQUENCY UP TO WHICH FREQUENCY RESPONSE IS DESIRED
FACTOR IS CONVERSION FACTOR FOR THERMOCOUPLE OUTPUT, IN MV, INTO TEMPERATURE
IN F. ITS UNITS ARE F/MV.

SENS IS SENSITIVITY OF RECORDING-CHANNEL FOR RESPONSE PULSE, MV/CM
FLOFAC IS CONVERSION FACTOR FOR CONTROL VALVE OUTPJT:

FOR REFLUX OR FEED VALVE ITS UNITS ARE, MM OF CHART/GPM FLOW RATE
FOR STEAM C.V. ITS UNITS ARE, MV OF VALVE-TRANSDUCER OUTPUT/INCH VALVE-
STEM TRAVEL

0002
0003

100 READ(1,101)DT1,DT2,DT3,DT4,WMAX,FACTOR,SENS,FLOFAC
IF(DT1)102,102,103

K1,K2 ARE NUMBER OF DATA POINTS READ OVER FIRST AND SECOND TIME-INTERVAL


```

C
C 0032 READ IN INITIAL, PEAK AND FINAL LAG VALUES OF RESPONSE DATA (FOR FORCING ON
C 0033 STEAM ONLY) FOR COMPUTING LAG-WINDOW FUNCTION
C 0034 READ(1,411) TO, TM, TP
C 0035 FORMAT(3F6.1)
C 411 REWRITE LAG-WINDOW FUNCTION DATA
C 0036 WRITE(3,412) TO, TM, TP
C 412 FORMAT(IX,'VALUES OF TO, TM, TP ARE', 33(F6.1,6X), 'RESP. ', /)
C
C 0037 USE LAG-WINDOW FUNCTION SUBROUTINE TO CORRECT OUTPUT PULSE DATA FOR
C 0038 FORCING ON STEAM ONLY
C 0039 CALL WINDOW(TO, TM, TP, K3, L2, L5, DT3, DT4, Y, YY)
C 0040 USE CORRECTED RESPONSE DATA AS TRUE RESPONSE DATA (STEAM FORCING ONLY)
C 0041 DO 407 I=1, L2
C 0042 Y(I)=YY(I)
C 407 WRITE RESPONSE PULSE DATA AFTER CORRECTING WITH LAG WINDOW FUNCTION
C 0039 WRITE(3,405)
C 405 FORMAT(//, ' FOLLOWING IS LAG_WINDOW CORRECTED RESPONSE_DATA: ', /)
C 0041 WRITE(3,406)(Y(I), I=1, L2)
C 0042 FORMAT(12(4X,F5.2), /)
C
C 0043 REDUCTION OF INTERVAL SIZE OF OUTPUT PULSE DATA
C 0044 REDUCTION OF FIRST TIME INTERVAL
C 0045 DO 311 I=1, L5
C 0046 II=I+1
C 0047 YY(I)=(Y(II)-Y(I))/2.0
C 0048 DO 312 J=1, 2
C 0049 Z=J
C 0050 II=(I-1)*2+J+1
C 0051 YY(II)=Y(I)+YY(I)*Z
C 311 CONTINUE
C 0052 REDUCTION OF SECOND TIME INTERVAL
C 0053 LK3=II
C 0054 DO 313 I=K3, L6
C 0055 II=I+1
C 0056 YY(I)=(Y(II)-Y(I))/4.0
C 0057 DO 314 J=1, 4
C 0058 Z=J
C 0059 II=(I-K3)*4+J+LK3
C 314 YY(II)=Y(I)+YY(I)*Z
C 313 CONTINUE

```

```

0060 C      YYY(1)=Y(1)
0061 C      KL2=II
0062 C      REPLACE ORIGINAL OUTPUT PULSE DATA AND TIME INTERVALS BY NEW DATA WITH
0063 C      REDUCED TIME INTERVAL
0064 C      DO 315 I=1, KL2
0065 C      Y(I)=YYY(I)
0066 C      DT3=DT3/2.0
0067 C      DT4=DT4/4.0
0068 C      K3=LK3
0069 C      L2=KL2
0070 C      L5=K3-1
0071 C      L6=L2-1
0072 C
0073 C      START COMPUTING AREA UNDER INPUT PULSE CURVE TO COMPUTE FREQUENCY CONTENT
0074 C      AT ZERO FREQUENCY
0075 C      C=X(I)/2.0
0076 C      DO 107 I=2, L3
0077 C      C=C+X(I)
0078 C      C=C+X(K1)/2.0
0079 C      CS=C*DT1
0080 C      C=X(K1)/2.0
0081 C      M=K1+1
0082 C      DO 108 I=M, L4
0083 C      C=C+X(I)
0084 C      C=C+X(L1)/2.0
0085 C      SQ=CS+C*DT2
0086 C      END OF COMPUTATION FOR AREA UNDER INPUT PULSE CURVE
0087 C
0088 C      START COMPUTING FREQUENCIES IN LOGARITHMIC SCALE
0089 C      MM=0
0090 C      DO 109 JJ=1, MN
0091 C      DO 110 II=2, 10
0092 C      J=9*(JJ-1)+II-1+MM
0093 C      ZZ=II
0094 C      W(J)=ZZ/(10.0**((NN-JJ)))
0095 C      CHECK FOR MAXIMUM DESIRED VALUE OF FREQUENCIES
0096 C      IF(W*AX-W(J))111,112,112
0097 C      CHECK FOR FREQUENCIES BETWEEN 0.01 AND 0.02 RAD/SEC RANGE AND THEN COMPUTE
0098 C      FREQUENCIES IN LINEAR SCALE IN THIS RANGE(5 INTERVALS)
0099 C      112 IF(W(J)-0.01)191,192,191

```

```

0089 C 192 DO 193 I=1,4
0090 Z=I
0091 J=J+1
0092 193 W(J)=0.01+0.002*Z
0093 MM=4
C C CHECK FOR FREQUENCIES BETWEEN 0.02 AND 0.03 RAD/SEC RANGE AND THEN COMPUTE
C FREQUENCIES IN LINEAR SCALE IN THIS RANGE(5 INTERVALS)
0094 191 IF(W(J)-0.02)194,195,194
0095 195 DO 196 I=1,4
0096 Z=I
0097 J=J+1
0098 196 W(J)=0.02+0.002*Z
0099 MM=8
0100 194 CONTINUE
0101 110 CONTINUE
0102 109 CONTINUE
0103 111 JI=J-1
C C END OF COMPUTATION OF FREQUENCIES IN LOGARITHMIC SCALE
C C
C C START COMPUTING FOURIER TRANSFORM OF PULSE DATA AT FREQUENCIES COMPUTED
C EARLIER TO OBTAIN GAIN,PHASE LAG AND FREQUENCY CONTENT
0104 DO 199 J=1,JI
C CHOOSE ONE FREQUENCY,IN ORDER,PROCEED WITH ALL COMPUTATIONS FOR THAT
C FREQUENCY BEFORE RETURNING TO INITIALISATION FOR COMPUTATION FOR NEXT
C FREQUENCY
C C
C C FIRST REDUCTION OF INPUT PULSE DATA IS STARTED
0105 T=0.0
0106 C=X(1)/2.0
0107 D=0.0
C C COMPUTATION OF FOURIER TRANSFORM OVER FIRST TIME INTERVAL ZONE OF INPUT
C PULSE
0108 DO 113 I=2,L3
0109 T=T+DT1
0110 WT=W(J)*T
0111 C=C+X(I)*COS(WT)
0112 D=D+X(I)*SIN(WT)
0113 T=T+DT1
0114 WT=W(J)*T
0115 CM=(X(K1)*COS(WT))/2.0

```

```

0116 DM=(X(K1)*SIN(WT))/2.0
0117 C=C+CM
0118 D=D+DM
C
0119 COMPUTE CORRECTION FACTOR FOR MODIFIED TRAPEZOIDAL RULE
0120 WDT1=W(J)*DT1/2.0
0121 IF(WDT1-0.10)171,172,172
0122 WST1=SIN(WDT1)
0123 WCL=(WST1/WDT1)**2
0124 GO TO 173
0125 171 WCL=1.0
0126 173 CS=C*DT1*WCL
DS=D*DT1*WCL
C
0127 COMPUTATION OF FOURIER TRANSFORM OVER SECOND TIME INTERVAL ZONE OF INPUT
0128 PULSE
0129 C=CM
0130 D=DM
0131 M=K1+1
0132 DJ 114 I=M,L4
0133 T=T+DT2
0134 WT=W(J)*T
0135 C=C+X(I)*COS(WT)
0136 D=D+X(I)*SIN(WT)
0137 114 D=D+X(I)*SIN(WT)
0138 TX=T+DT2
0139 WT=W(J)*TX
0140 C=C+X(L1)*COS(WT)/2.0
0141 D=D+X(L1)*SIN(WT)/2.0
0142 COMPUTE CORRECTION FACTOR FOR MODIFIED TRAPEZOIDAL RULE
0143 WDT2=W(J)*DT2/2.0
0144 IF(WDT2-0.10)174,174,175
0145 WST2=SIN(WDT2)
0146 WC2=(WST2/WDT2)**2
0147 GO TO 176
0148 174 WC2=1.0
0149 176 CS=CS+C*DT2*WC2
0150 CS=REAL PART OF FOURIER TRANSFORM OF INPUT PULSE
0151 DS=DS+D*DT2*WC2
0152 DS=IMAGINARY PART OF FOURIER TRANSFORM OF INPT PULSE
0153 END OF COMPUTATION OF FOURIER TRANSFORM OF INPUT PULSE DATA
0154 C
0155 START COMPUTATION OF FOURIER TRANSFORM OF OUTPUT PULSE DATA

```

```

0147 T=0.0
0148 A=0.0
0149 B=0.0
C COMPUTATION OF FOURIER TRANSFORM OVER FIRST TIME INTERVAL ZONE OF OUTPUT
C PULSE
0150 DO 115 I=2,L5
0151 T=T+DT3
0152 WT=W(J)*T
0153 A=A+Y(I)*COS(WT)
0154 B=B+Y(I)*SIN(WT)
0155 T=T+DT3
0156 WT=W(J)*T
0157 AM=(Y(K3)*COS(WT))/2.0
0158 BM=(Y(K3)*SIN(WT))/2.0
0159 A=A+AM
0160 B=B+BM
C COMPUTE CORRECTION FACTOR FOR MODIFIED TRAPEZOIDAL RULE
0161 WDT3=W(J)*DT3/2.0
0162 IF(WDT3-0.10)177,177,178
0163 178 WST3=SIN(WDT3)
0164 WC3=(WST3/WDT3)**2
0165 GO TO 179
0166 177 WC3=1.0
0167 179 AS=A*DT3*WC3
0168 BS=B*DT3*WC3
C COMPUTATION OF FOURIER TRANSFORM OVER SECOND TIME INTERVAL ZONE OF OUTPUT
C PULSE
0169 A=AM
0170 B=BM
0171 N=K3+1
0172 DO 116 I=N,L6
0173 T=T+DT4
0174 WT=W(J)*T
0175 A=A+Y(I)*COS(WT)
0176 B=B+Y(I)*SIN(WT)
0177 TY=T+DT4
0178 WT=W(J)*TY
0179 A=A+Y(L2)*COS(WT)/2.0
0180 B=B+Y(L2)*SIN(WT)/2.0
C COMPUTE CORRECTION FACTOR FOR MODIFIED TRAPEZOIDAL RULE

```

```

C
0181 WDT4=W(J)*DT4/2.0
0182 IF(WDT4-0.10)180,180,181
0183 181 WST4=SIN(WDT4)
0184 WC4=(WST4/WDT4)**2
0185 GO TO 182
0186 180 WC4=1.0
0187 182 AS=AS+A*DT4*WC4
C AS=REAL PART OF FOURIER TRANSFORM OF OUTPUT PULSE
C BS=BS+B*DT4*WC4
C HS=IMAGINARY PART OF FOURIER TRANSFORM OF OUTPUT PULSE
C END OF COMPUTATION OF FOURIER TRANSFORM OF OUTPUT PULSE DATA
C
C COMPUTE MAGNITUDE PHASE LAG ANGLE OF OUTPUT PULSE FOURIER TRANSFORM, USING
C SUBROUTINE THETA
C RE=AS
C XIM=RS
C CALL THETA(RE,XIM,XMR,ANGLE)
C COMPUTE MAGNITUDE IN PROPER UNITS( F*SEC.)
0192 RESMR(J)=XMR*SENS*FACTOR/10.0
0193 RESANG(J)=ANGLE
C COMPUTE MAGNITUDE PHASE LAG ANGLE OF INPUT PULSE FOURIER TRANSFORM, USING
C SUBROUTINE THETA
C RE=CS
C XIM=DS
C CALL THETA(RE,XIM,XMR,ANGLE)
C COMPUTE MAGNITUDE IN PROPER UNITS:
C
C GPM*SEC.(FOR FORCING ON REFLUX OR FEED)
C INCH*SEC.(FOR FORCING ON STEAM)
C
C USE FOLLOWING FORMULA FOR FORCING ON REFLUX OR FEED
C FORMR(J)=XMR/FLOFAC
C USE FOLLOWING FORMULA FOR FORCING ON STEAM
C FORMR(J)=XMR*SENIN/(FLOFAC*10.0)
C FORMANG(J)=ANGLE
C COMPUTE DIRECTLY GAIN AND PHASE LAG OF THE SYSTEM
C Q=CS*CS+DS*DS
C RE=(AS*CS+BS*DS)/Q
C XIM=(BS*CS-AS*DS)/Q
C USE SUBROUTINE THETA TO COMPUTE MAGNITUDE RATIO AND ANGLE
C CALL THETA(RE,XIM,XMR,ANGLE)
C FOR PULSE FORCING ON REFLUX OR FEED,USE FOLLOWING FORMULA TO OBTAIN GAIN

```

```

C      IN PROPER UNITS( F/GPM)
C      XMR=XMR*SENS*FACTOR*FLOFAC/10.0
C
C      FOR PULSE FORCING ON STEAM, USE FOLLOWING FORMULA TO OBTAIN GAIN IN PROPF
C      UNITS( F/INCH)
0203  XMR=XMR*SENS*FACTOR*FLOFAC/SENIN
0204  PHASE(J)=ANGLE
0205  DAR(J)=XMR
0206  DARN(J)=DAR(J)/DAR(I)
C      COMPUTE NORMALISED FREQUENCY CONTENT
0207  SW=SQRT(Q)
0208  199 SWN(J)=SW/SJ
C      END OF COMPUTATION OF GAIN, PHASE LAG AND FREQUENCY CONTENT FOR PARTICULAR
C      FREQUENCY AND GO OVER AGAIN IN DO-LOOP FOR NEXT FREQUENCY
C      END OF COMPUTATIONS FOR ALL FREQUENCIES UP TO WMAX(MAXIMUM FREQUENCY)
C
0209  WRITE(3,147)TX
0210  WRITE(3,148)TY
C      WRITE RESPONSE PULSE DATA WITH REDUCED TIME INTERVALS.
0211  WRITE(3,321)
0212  WRITE(3,324)L2,DT3,DT4
0213  WRITE(3,325)(VY(N),N=1,L2)
0214  WRITE(3,149)WMAX,MN,NN
0215  WRITE(3,202)FACTOR
C      WRITE FREQUENCY CONTENT OF INPUT PULSE AND SYSTEM GAIN AND PHASE LAG AT
C      VARIOUS FREQUENCIES
0216  WRITE(3,150)
0217  WRITE(3,151)
0218  WRITE(3,203)
0219  DO 161 I=1,JI
0220  161 WRITE(3,152)I,W(I),DAR(I),SWN(I),DARN(I),PHASE(I)
C      WRITE MAGNITUDES AND ANGLES OF INPUT AND RESPONSE PULSE FOURIER TRANSFORMS
C      AT VARIOUS FREQUENCIES
0221  WRITE(3,341)
0222  WRITE(3,342)
0223  WRITE(3,343)
0224  DO 344 I=1,JI
0225  344 WRITE(3,345)I,W(I),FORMR(I),FORANG(I),RESMR(I),RESANG(I)
0226  WRITE(3,156)
0227  WRITE(3,157)

```

```

0228 C GO BACK TO INITIAL STAGE TO REDUCE NEXT EXPERIMENTAL PULSE-TEST DATA
0229 C GO TO 100
0230 101 FORMAT(2F4.2,2F4.1,F6.3,F4.1,F4.2,F5.1)
0231 104 FORMAT(4I3,3I2,2F3.1)
0232 105 FORMAT(20F4.1)
0233 106 FORMAT(20F4.1)
129 FORMAT(1H1,' THE FOLLOWING PULSE TEST DATA IS FOR EVALUATION OF
IFREQUENCY RESPONSE,USING MODIFIED TRAPEZOIDAL RULE:',//)
C FOLLOWING IS FORMAT FOR FEED OR REFLUX FORCING
C 130 FORMAT(1X,'FEED/REFLUX C.V. IS RANDOM_PULSED AT ... GPM WITH FLOW
IFACTOR OF ',F5.1,' MM OF CHART READING PER GPM OF FLUID FLOW.')
```

```

C FOLLOWING IS FORMAT FOR STEAM FORCING
C 130 FORMAT(1X,'STEAM C.V. IS RANDOMLY PULSED FROM TO (PSIG)WITH'
1,F5.1,' MV OF VALVE-TRANSDUCER OUTPUT PER INCH VALVE-STEM TRAVEL')
```

```

C 131 FORMAT(1X,'OUTPUT RESPONSE IS OF TRAY NO. ',I2,'(FROM THE TOP) TE
MPERATURE AT ..... F',////)
132 FORMAT(1X,'RECORDING CHANNEL DATA IS ',//)
133 FORMAT(5X,'CHART',35X,'SENSITIVITY',/)
134 FORMAT(5X,'SPEED',20X,'CHANNEL 1',20X,'CHANNEL 2')
```

```

135 FORMAT(31X,'(INPUT)',21X,'(OUTPUT)')
136 FORMAT(3X,'(MM/SEC)',19X,'(MV/CM)',21X,'( MV/CM)',////)
201 FORMAT(5X,F3.1,23X,F4.1,24X,F6.4)
137 FORMAT(//,' INPUT DATA IS',//)
138 FORMAT(1X,'INTERVAL WIDTHS ARE ,DT1=',F4.2,' AND DT2=',F4.2)
139 FORMAT(//,' THE ',I3,' VALUES OF INPUT PULSE DATA ARE',/)
140 FORMAT(12(4X,F5.2),/)
141 FORMAT(//,' INPUT PULSE K1 AND K2 ARE ',I3,' AND ',I3,/)
142 FORMAT(//,' OUTPUT DATA IS',//)
143 FORMAT(1X,'INTERVAL WIDTHS ARE,DT3=',F4.2,' AND DT4=',F5.2,//)
144 FORMAT(1X,' THE ',I3,' VALUES OF RESPONSE DATA ARE',/)
145 FORMAT(12(4X,F5.2),/)
146 FORMAT(//,' RESPONSE CURVE K3 AND K4 ARE ',I3,' AND ',I3)
147 FORMAT(//,' INPUT PULSE WIDTH IS,TX=',F7.3,//)
148 FORMAT(1X,'RESPONSE CURVE WIDTH IS ,TY=',F8.3,////)
149 FORMAT(1X,'WMAX IS=',F6.3,5X,'MN IS=',I2,5X,'NN IS=',I2,//)
202 FORMAT(1X,'FACTOR AT TRAY TEMPERATURE IS ',F4.1,' F/MV ',////)
150 FORMAT(1H1,////,' LISTED BELOW ARE FREQUENCY CONTENT(NORM),DYNA
MIC AMPLITUDE RATIO(ABS AND NORM) AND PHASE LAG.')
```

```

151 FORMAT(8X,'I',10X,'W(I)', 9X,'DAR(I)', 8X,'SAY(I)', 8X,'DAR(NOR4)')
1, 4X,'PHASE LAG')
```

```

C
C FOLLOWING IS FORMAT FOR FEED OR REFLUX FORCING
C 203 FORMAT(20X,'RADIAN/SEC.',10X,'F/GPM ',53X,'DEGREES',/)
C FOLLOWING IS FORMAT FOR STEAM FORCING
C 203 FORMAT(14X,'RADIAN/SEC.',7X,'F/INCH',36X,'DEGREES')
152 FORMAT(6X,I3,7X,5(F8.4,6X))
156 FORMAT(///,'DATE',20X,'EXPERIMENT CODE',/)
157 FORMAT(1X,'COMMENTS',//////////)
321 FORMAT(1X,'LISTED BELOW IS LAG WINDOW CORRECTED RESPONSE DATA WITH
1 REDUCED TIME INTERVALS:',/)
324 FORMAT(1X,'THE',I3,'VALUES OF OUTPUTDATA WITH DT3 AND DT4 ',F5.3,
1' AND ',F6.3,' SECONDS RESP. ARE...',/)
325 FORMAT(12(4X,F5.2))
341 FORMAT(1H1,////////,' LISTED BELOW ARE MAGNITUDES AND ANGLES OF F
FOURIER TRANSFORMS OF BOTH INPJT AND OUTPUT PULSES.')
```

```

0258
0259
0260
0261
0262
0263
0264
0265
0266
0267
0268
0269
0270
```

```

C 342 FORMAT(8X,I',10X,'W(I)',8X,'FORMR',10X,'FORANG',8X,'RESVR',8X,
1'RESAVG')
```

```

C FOLLOWING IS FORMAT FOR FEED OR REFLUX FORCING
C 343 FFORMAT(20X,'RADIAN/SEC',6X,' (GPM#SEC) ',7X,'(DEGREES)',8X,'( F
1*SEC)'8X,'(DEGREES)')
```

```

C FOLLOWING IS FORMAT FOR STEAM FORCING
C 343 FORMAT(16X,'RADIAN/SEC',2X,' (INCHES#SEC)',3X,'(DEGREES)',4X,'( F
1*SEC)'6X,'(DEGREES)')
```

```

345 FORMAT(6X,I3,7X,5(F8.4,6X))
102 RETURN
END
```



```

C
C
C
C
C
0001 SUBROUTINE TO COMPUTE LAG-WINDOW FUNCTION
0002 SUBROUTINE WINDOW(TO, TM, TP, K3, L2, L5, DT3, DT4, Y, YY)
0003 DIMENSION Y(200), YY(200)
0004 TLAM=(TM-TP)/(TM-TO)
0005 COMPUTE CORRECTED RESPONSE DATA IN FIRST TIME INTERVAL ZONE
0006 T=0.0
0007 DO 403 I=1,L5
0008 IF(T.GE.TP)GO TO 411
0009 USE FOLLOWING FORMULA WHEN DATA TREATED IS BEFORE FIRST PEAK
0010 YY(I)=Y(I)
0011 GO TO 412
0012 USE FOLLOWING FORMULA WHEN DATA TREATED IS AFTER FIRST PEAK
0013 YY(I)=Y(I)*(1-((T+TLAM*(TM-TO)-TM)/((TLAM*(TM-TO)))*2)
0014 T=T+DT3
0015 403 CONTINUE
0016 COMPUTE CORRECTED RESPONSE DATA IN SECONVD TIME INTERVAL ZONE
0017 DO 404 I=K3,L2
0018 IF(T.GE.TP)GO TO 413
0019 USE FOLLOWING FORMULA WHEN DATA TREATED IS BEFORE FIRST PEAK
0020 YY(I)=Y(I)
0021 GO TO 414
0022 USE FOLLOWING FORMULA WHEN DATA TREATED IS AFTER FIRST PEAK
0023 YY(I)=Y(I)*(1-((T+TLAM*(TM-TO)-TM)/((TLAM*(TM-TO)))*2)
0024 T=T+DT4
0025 404 CONTINUE
0026 RETURN
0027 END

```

COMPUTER SAMPLE OUTPUT (Frequency Response of Tray 6 for forcing on the Steam)
 LISTED BELOW ARE FREQUENCY CONTENT(NORM), DYNAMIC AMPLITUDE RATIO(ABS AND NORM) AND PHASE LAG.

I	W(I) RADIANS/SEC.	DAR(I) F/INCH	SWN(I)	DAR(NORM)	PHASE LAG DEGREES
1	0.0002	42.9456	1.0000	1.0000	3.7555
2	0.0003	42.8993	1.0000	0.9989	5.6326
3	0.0004	42.8346	1.0000	0.9974	7.5079
4	0.0005	42.7516	0.9999	0.9955	9.3821
5	0.0006	42.6505	0.9999	0.9931	11.2544
6	0.0007	42.5311	0.9999	0.9903	13.1245
7	0.0008	42.3940	0.9998	0.9872	14.9919
8	0.0009	42.2388	0.9998	0.9835	16.8565
9	0.0010	42.0664	0.9998	0.9795	18.7175
10	0.0020	39.4350	0.9991	0.9183	37.0517
11	0.0030	35.4212	0.9979	0.8248	54.5752
12	0.0040	30.5236	0.9962	0.7107	70.7797
13	0.0050	25.3289	0.9941	0.5898	85.0488
14	0.0060	20.4176	0.9915	0.4754	96.7010
15	0.0070	16.2550	0.9884	0.3785	105.2120
16	0.0080	13.0736	0.9849	0.3044	110.6582
17	0.0090	10.8072	0.9809	0.2515	113.9805
18	0.0100	9.1797	0.9765	0.2138	116.3331
19	0.0120	6.9629	0.9663	0.1621	118.9214
20	0.0140	5.9083	0.9543	0.1375	119.6363
21	0.0160	5.3261	0.9406	0.1240	126.5581
22	0.0180	4.2760	0.9252	0.0996	135.6586
23	0.0200	3.3274	0.9082	0.0775	136.0608
24	0.0220	3.0383	0.8896	0.0707	135.7397
25	0.0240	2.6910	0.8695	0.0627	141.7792
26	0.0260	2.2490	0.8480	0.0524	143.7948
27	0.0280	2.0514	0.8252	0.0478	146.0123
28	0.0300	1.6934	0.8011	0.0394	152.8559
29	0.0400	0.4095	0.6648	0.0095	188.1578
30	0.0500	0.8464	0.5112	0.0197	86.1973
31	0.0600	1.6506	0.3534	0.0384	189.2194
32	0.0700	2.0705	0.2059	0.0482	177.5182
33	0.0800	3.4169	0.0932	0.0796	226.1004
34	0.0900	1.0213	0.0944	0.0238	215.4088
35	0.1000	0.5298	0.1575	0.0123	342.5264
36	0.2000	1.7685	0.0497	0.0412	75.4712

COMPUTER SAMPLE OUTPUT (Continued)

LISTED BELOW ARE MAGNITUDES AND ANGLES OF FOURIER TRANSFORMS OF BOTH INPUT AND OUTPUT PULSES.

I	W(I)	RADIAN/SEC	FMR (INCHES*SEC)	FORANG (DEGREES)	RESMR (F*SEC)	RESANG (DEGREES)
1	0.0002	9.0059	0.4681	386.7529	4.2238	
2	0.0003	9.0058	0.7022	386.3411	6.3348	
3	0.0004	9.0056	0.9362	385.7524	8.4441	
4	0.0005	9.0054	1.1703	384.9963	10.5524	
5	0.0006	9.0052	1.4043	384.0754	12.6587	
6	0.0007	9.0049	1.6384	382.9885	14.7629	
7	0.0008	9.0046	1.8725	381.7395	16.8644	
8	0.0009	9.0042	2.1065	380.3281	18.9630	
9	0.0010	9.0038	2.3406	378.7581	21.0580	
10	0.0020	8.9974	4.6810	354.8132	41.7328	
11	0.0030	8.9858	7.0212	318.3225	61.5965	
12	0.0040	8.9719	9.3611	273.8545	80.1408	
13	0.0050	8.9528	11.7005	226.7635	96.7493	
14	0.0060	8.9294	14.0394	182.3181	110.7404	
15	0.0070	8.9019	16.3775	144.7003	121.5895	
16	0.0080	8.8702	18.7149	115.9649	129.3731	
17	0.0090	8.8343	21.0513	95.4746	135.0315	
18	0.0100	8.7944	23.3866	80.7300	139.7194	
19	0.0120	8.7023	28.0536	60.5936	146.9747	
20	0.0140	8.5943	32.7148	50.7783	152.3508	
21	0.0160	8.4708	37.3691	45.1163	163.9268	
22	0.0180	8.3322	42.0153	35.6279	177.6739	
23	0.0200	8.1789	46.6520	27.2143	182.7131	
24	0.0220	8.0116	51.2781	24.3420	187.0181	
25	0.0240	7.8309	55.8922	21.0726	197.6718	
26	0.0260	7.6374	60.4925	17.1768	204.2876	
27	0.0280	7.4318	65.0773	15.2459	211.0900	
28	0.0300	7.2148	69.6446	12.2177	222.5008	
29	0.0400	5.9876	92.1282	2.4518	280.2859	
30	0.0500	4.6040	113.6527	3.8966	199.8501	
31	0.0600	3.1827	133.1420	5.2532	322.3611	
32	0.0700	1.8540	147.0654	3.8387	324.5835	
33	0.0800	0.8396	137.4137	2.8687	3.5144	
34	0.0900	0.8505	86.3124	0.8687	301.7212	
35	0.1000	1.4186	83.5118	0.7516	66.0383	
36	0.2000	0.4476	254.4110	0.7917	329.8821	

APPENDIX D

D.1 COMPARISON OF STEADY STATE GAIN OBTAINED FROM THE PULSE TEST AND THE STEP TEST:

Notation:

SP Size of step forcing.

$\Delta\theta$ Change in temperature of tray with step forcing of size SP, °F.

TABLE 22

Steady State Gain from the Pulse Test and the Step Test for the Forcing on Reflux.

SP = $\frac{5}{495} \approx 0.01$ gpm at steady state reflux flow rate of 0.2 gpm.

Tray	$\Delta\theta$	Steady State Gain, °F/gpm	
		(Pulse Test)	(Step Test)
1	0.4	29	40
2	0.6	62	60
3	0.9	92	90
4	1.3	135	130
6	1.6	172	160
8	0.6	62	60
9	0.3	21	30
10	-	8.2	-

TABLE 23

Steady State Gain from the Pulse Test and the Step Test for the Forcing on Feed.

$$SP = \frac{8}{380} \approx 0.021 \text{ gpm at steady state feed flow rate of } 0.38 \text{ gpm.}$$

Tray	$\Delta\theta$	Steady State Gain, $^{\circ}F/gpm$	
		(Pulse Test)	(Step Test)
6	0.9	38	42.8
8	1.0	40	47.6
9	0.9	42	42.8
10	0.5	19	23.8

TABLE 24

Steady State Gain from the Pulse Test and the Step Test for the Forcing on Steam.

$$SP = \frac{5 \times 0.5}{96} \approx 0.026 \text{ inches of valve stem travel at 9 psig air signal to the valve.}$$

Tray	$\Delta\theta$	Steady State Gain, $^{\circ}F/inch$		
		with Lag-window	without Lag-window	(Step Test)
10	0.3	4.0	4.7	11.5
9	0.3	10.3	12.1	11.5
8	0.9	33	39	34.6
6	1.2	44	49	46.2
4	1.2	43	51	46.2
3	0.9	31.5	36.5	34.6
2	0.6	21	26	23.0
1	0.4	16	19.5	15.4

D.2 COMPARISON OF FREQUENCY RESPONSE OBTAINED FROM THE PULSE TEST AND THE SINUSOIDAL TEST FOR THE FORCING ON STEAM:

Notation:

PT Pulse test

ST Sinusoidal test

TABLE 25

Tray	Frequency Rad/sec	Gain, °F/inch		Phase Lag, degrees	
		PT	ST	PT	ST
10	0.007	3.6	4.2	34	32
	0.01	3.15	3.5	49	55
	0.02	1.65	2.1	78	—
9	0.007	9.2	8.8	45	55
	0.01	8.0	7.8	63	60
	0.02	4.0	4.2	103	99
	0.03	2.1	2.56	115	110
	0.04	1.45	2.0	118	125
8	0.007	16.3	13.0	95	82
	0.01	9.0	8.7	110	98
	0.02	4.0	6.4	120	116
	0.03	3.0	4.26	129	126
	0.04	2.4	2.3	143	150
	0.05	2.0	1.8	158	—

TABLE 25 (Continued)

Tray	Frequency Rad/sec	Gain, °F/inch		Phase Lag, degrees	
		PT	ST	PT	ST
6	0.007	16.5	20.0	102	96
	0.01	9.5	13.0	115	110
	0.02	3.4	5.4	136	133
	0.03	1.7	2.56	153	156
4	0.007	12.6	11.3	90	98
	0.01	8.2	10.0	85	108
	0.02	4.5	6.0	88	133
	0.03	3.2	3.4	90	120
	0.04	2.5	2.0	94	-
	0.05	1.8	1.7	95	-
3	0.007	10.43	10.8	85	87
	0.01	8.7	9.3	93	105
	0.02	3.8	3.4	109	112
	0.03	2.35	2.45	119	118
	0.04	1.45	1.2	125	-
2	0.007	6.6	7.2	78	93
	0.01	5.6	6.7	75	100
	0.02	2.9	3.4	103	107
	0.03	1.9	2.1	128	118

The sinusoidal test results for tray 1 could not be obtained because of the very small amplitude of sinusoidal response.