To the Graduate Council:

I am submitting herewith a thesis written by Wu Yan entitled "Design of a Dynamic Compensated Temperature Sensor." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Nuclear Engineering.

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E. M. Katz, Major Professor

We have read this thesis
and recommend its acceptance:

L F Miller

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Accepted for the Council:

Associate Vice Chancellor
and Dean of The Graduate School

DESIGN OF A DYNAMIC COMPENSATED TEMPERATURE SENSOR

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Wu Yan

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DEDICATION

This thesis is dedicated to my wife, Qin Wan, my parents, Mrs. Kailian Wu and Mr. Lirong Yan, my brother, Dr. Xinyuan Wu, and my sister, Mrs. Fu Yan. To each I owe so much.

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Last, but not least, I wish to thank my wife, Qin Wan, for her loving support and patience during my graduate study.

ABSTRACT

This research describes the development of a fast responding temperature sensor, the Dynamic Compensated Temperature Sensor (DCTS). The signal compensated technique was used to create a compensated signal that has a shorter time constant than that of the traditional temperature sensors.

This research developed the general theoretical analysis of the DCTS in the Laplace domain and the time domain. It also describes the analysis, design, and construction of two types of compensated sensors: the Dynamic Compensated Sensor Using Independent Signals (DCI) and the Dynamic Compensated Sensor Using Lagged Signals (DCL). Through the discussion of these two kinds of new sensors, it is determined that the DCL has better behavior than the DCI.

Experiments were performed with the DCL and the results show that the DCL is indeed faster than other temperature sensors and there is no overshoot.

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CHAPTER I

INTRODUCTION

1.1 Problem Statement

Finite. Limited. We must remember that the Earth's natural resources are not unlimited. Therefore, we must constantly investigate alternative sources of power. One of the most viable alternatives is nuclear power. Since the 1950's, nuclear power has been used for generation of electricity, and nearly eight hundred nuclear power plants have been built in the world.

In a nuclear power plant, temperature measurement plays an important role in safety and control systems because there is a huge amount of heat transfer occurring in the various subsystems of the plant. It is essential that reliable and quick temperature measurements maintain the delicate heat balance within the safe and economical range of operation of the plant.

There is a time lag between the actual temperature change and the temperature sensor's response to it. The amount of lag is governed by the rate at which heat diffuses from the environment through the sensor interior. This lag may have a major impact when the sensor is used for applications such as providing control system signals, providing test data for subsequent interpretation, and providing safety shutdown or

feedback signals.

1.2 Project Description

Since in the nuclear power industry it is desirable to have a fast responding sensor, the goal of this project is to design, construct, and test a Dynamic Compensated Temperature Sensor (DCTS) based on signal dynamic compensation technology.

The dynamic response of a resistance temperature detector (RTD) or of a thermocouple (TC) is commonly characterized by the sensor's time constant, τ. The time constant τ is defined as the time to reach 63.2 percent of the final change in indicated temperature for a step change in temperature input. (See Figure 1.1).

The signal dynamic compensation method uses two signals, each with a different time constant, to achieve an enhanced compensated temperature response by creating the following signal:

$$T_C(t) = kT_f(t) - (k-1)T_s(t) , \tag{1.1}$$

where

$T_C(t)$ = compensated temperature signal,

$T_f(t)$ = fast temperature signal,

$T_s(t)$ = slow temperature signal,

k = a constant.

The DCTS system is shown schematically in Figure 1.2.

In this project, two methods of generating the $T_s(t)$

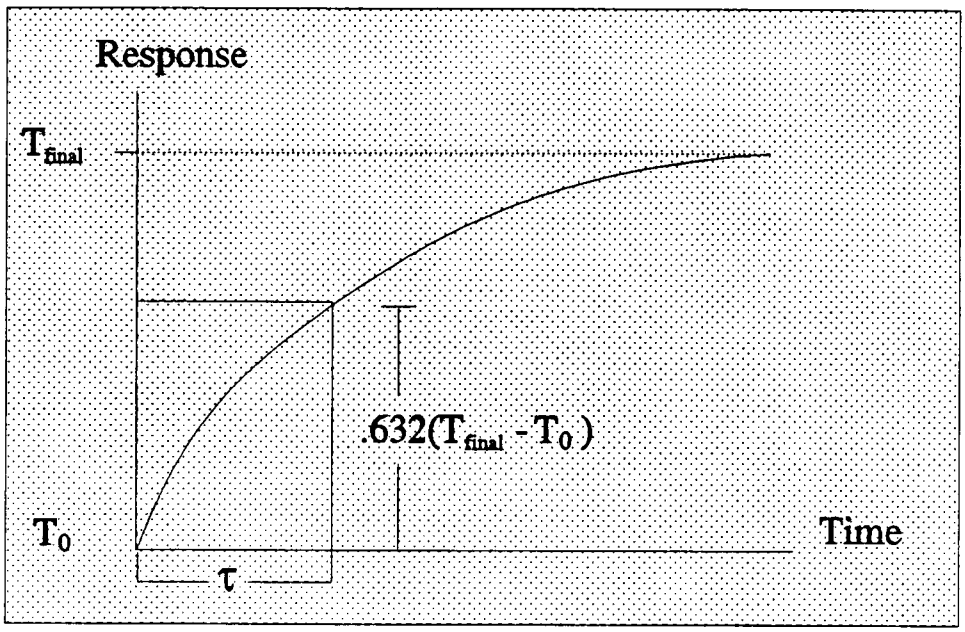


Figure 1.1 Definition of Response Time

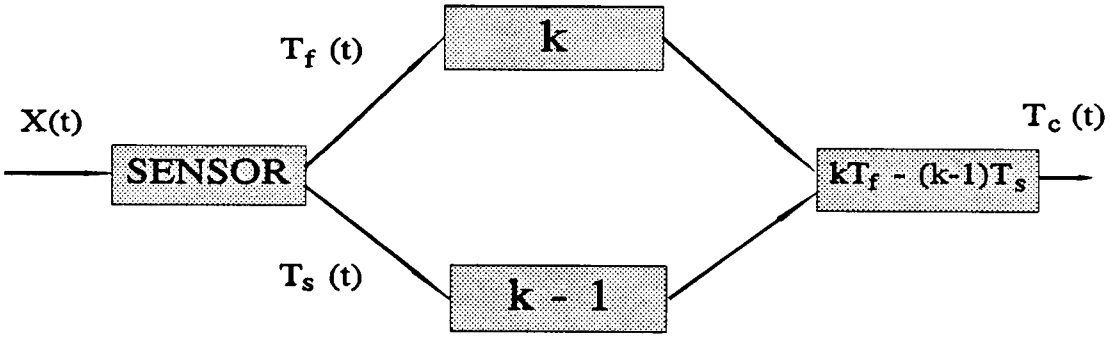


Figure 1.2 The DCTS System

signal were evaluated. One is using independent signals (DCI). Another is to use lagged signals (DCL). In this project, the analysis and experiments are performed with thermocouple. However, this method is also applicable to resistance thermometers.

Some scientists in European have also done similar work to reduce the time lag of a temperature sensor. Scientists in England, H. Rosemany Taylor and Hector A Navarro, reported the possibility of reducing temperature sensor time constant by using a digital compensation filter in 1983. However, there is no further discussion about how to design the compensated filter in their paper.

Recently, Polish scientists L. Michalski and K. Eckersdorf (1991) reported the principle and methods of using corrector circuits to correct the dynamic errors of temperature sensor in their book "Temperature Measurement." Three types of correctors: passive corrector, active corrector, and adaptive corrector have been evaluated. The active corrector is similar to the compensated circuit developed in this project. However, the compensated temperature sensor is developed based on the signal compensated technology while the corrector circuits is constructed based on the design of a special corrector transfer function to improve the dynamic behavior of a temperature sensor.

1.3 Outline of the Thesis

This report contains five chapters. Chapter II includes a general introduction to the thermocouple, a thermal model of TCs, and the theoretical analysis of the Dynamic Compensated Temperature Sensor (DCTS). In the analysis of the DCTS, DCTS with independent signals and DCTS with lagged signals are discussed separately. Through the analysis, we can show that the DCTS with Lagged Signals is the better design of the DCTS.

Chapter III describes the experimental analysis of the DCTS with lagged signals. It includes the types of tests, DCTS construction, and testing facilities.

The theoretical and experimental analysis and results regarding the DCTS performance are presented in Chapter IV.

Chapter V presents conclusions and recommendations.

CHAPTER II

THEORETICAL ANALYSIS

2.1 Thermocouples

A: Introduction

Thermocouples (TCs) have been used for measuring temperature since the early nineteenth century. They were developed by implementing the Seebeck effect discovered by T. J. Seebeck in 1821. If two dissimilar metals are joined together at one end (measurement junction), and they are placed in a thermal gradient, a voltage is generated across the wires at the other end. This is called the Seebeck effect. The voltage is a function of the temperature difference between the measurement junction and the reference junction. Thermocouples provide a means for sensing temperature in many processes: in nuclear reactors, aeronautical systems, power systems, refineries, and others.

A thermocouple is constructed by mechanically joining, welding, or brazing two metallic wires to form the measurement junction. The wires are typically 0.5 to 1.0 mm in diameter, although some special TCs can be made with wire smaller than a human hair. They are usually electrically insulated by cement or powder. The most commonly used powders are aluminum

oxide (Al_2O_3) and magnesium oxide (MgO). The sensing wires and insulator are often protected by a stainless steel sheath. Figure 2.1 shows a typical multilayered structure of a sheathed thermocouple.

TCs are simple, inexpensive, versatile, durable, and accurate. They can measure temperatures between -183°C (cryogenic thermocouples) and 2500°C (refractory thermocouples)[2].

B: Basic Circuit Theory

When a thermocouple is placed in a temperature gradient, (i.e., there exists a temperature difference between the Measuring Junction [MJ] and the Reference Junction [RJ]) an electromotive force (**emf**) is generated and can be measured at the reference junction. This **emf** is roughly proportional to the temperature difference. The Seebeck coefficient of a material is defined as the potential difference established along a wire of that material by the application of a unit temperature difference. This coefficient has the unit of volt/^{0}C, and it is called the thermoelectric power of the material. The **emf** can be calculated in terms of the difference in Seebeck coefficients of both wires and the temperature difference as[2]

$$V=(S_A-S_B)(T_M-T_R)\ , \qquad (2.1)$$

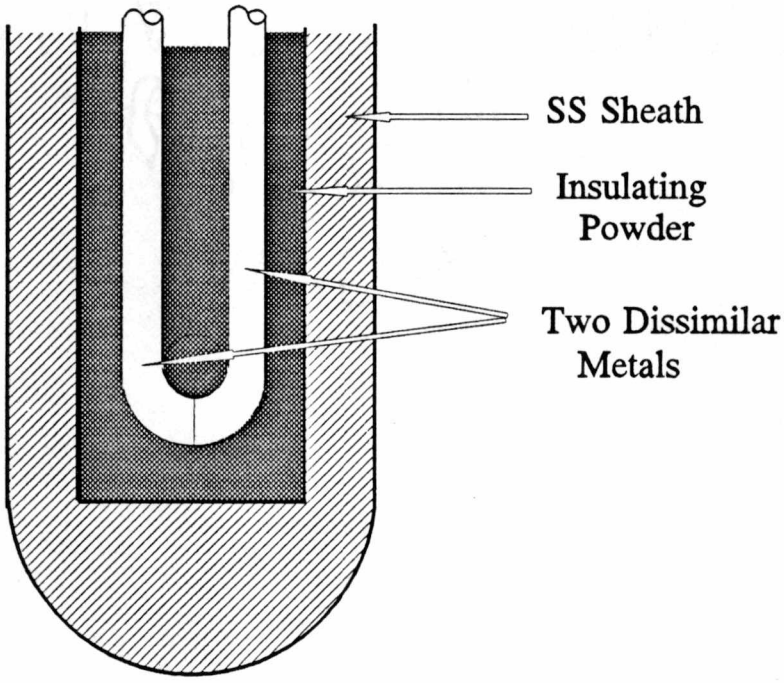


Figure 2.1 Typical Structure of a Sheathed Thermocouple

where

V = **emf** generated at the open end (volts),

T_M = MJ temperature (^{0}C),

T_R = RJ temperature (^{0}C),

S_A = Seebeck coefficient of wire A (volts/^{0}C),

S_B = Seebeck coefficient of wire B (volts/^{0}C).

The basic thermocouple circuit is shown schematically in Figure 2.2.

Two types of Seebeck coefficients are used. The first is the absolute Seebeck coefficient, which is a property of the material. It is denoted by S_A for material A and S_B for material B. The second is the relative Seebeck coefficient (S_{AB}) defined by $S_{AB} = S_A - S_B$. Therefore, Equation (2.1) can be rewritten as

$$V=S_{AB}(T_M-T_R) . \tag{2.2}$$

Equations (2.1) and (2.2) are true only if S_A and S_B are constants between T_M and T_R. Typical thermocouples, however, do not behave in such a linear fashion. Consequently, high order polynomials based on fitting high precision experimental temperature-emf data points have been developed to describe the true relationship between the emf and temperature.

2.2 Resistance Temperature Detectors

In 1887, H. L. Callendar published the paper entitled "On

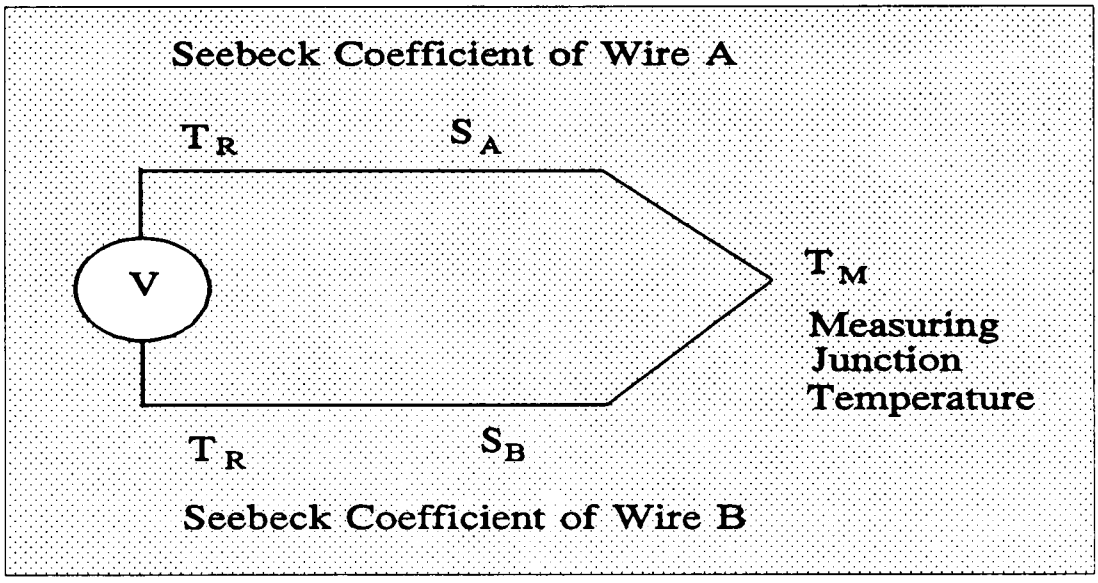


Figure 2.2 Basic Thermocouple Circuit

practical measurement of temperature", which may be regarded as the beginning of resistance thermometry.

The principle of a resistance thermometer is based upon the dependence of the resistance of metal conductors upon temperature. As the temperature of a metal increases, the metal resistance increases too. The electric resistance of the metal is expresses as[2]

$$R = \frac{r \times L}{A} \tag{2.3}$$

where

R = electric resistance (ohms)

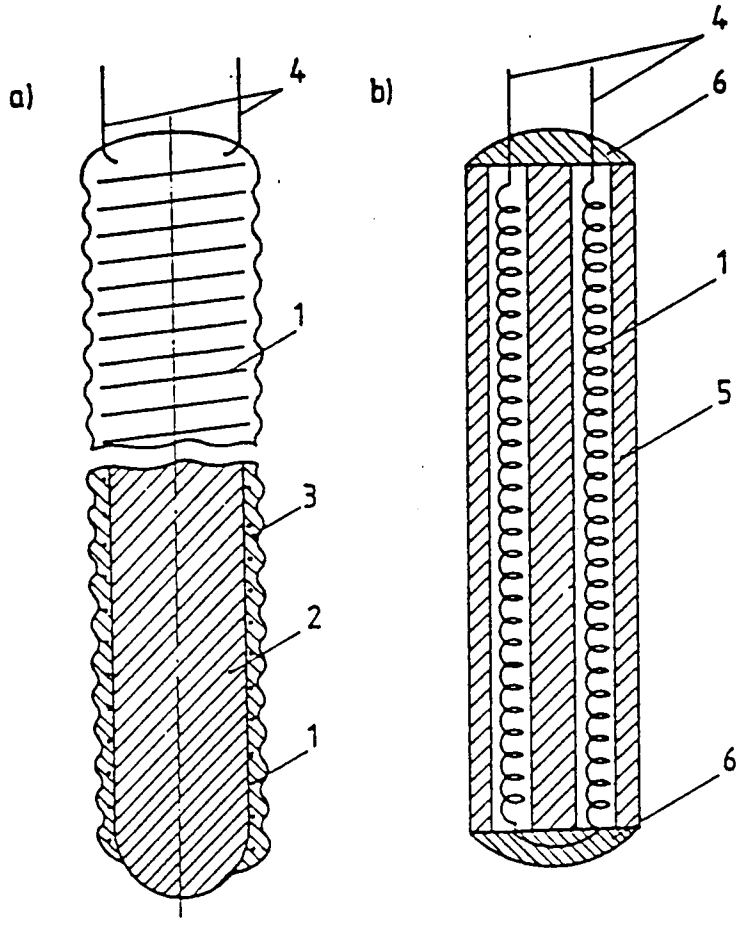
r = resistivity (ohm.cm)

L = length (cm)

A = cross sectional area (cm^2).

Resistance thermometer detectors (RTD) are some certain pure metals or semiconductors used as thermometers routinely. Metal selection for an RTD is usually based on practical resistivity, chemical inertness with respect to other constituents, large temperature coefficient, and freedom from strain effects on resistance.

RTDs are manufactured in a wide range of types. The general purpose detectors have wire-wound elements, thin film elements are becoming increasingly popular. Figure 2.3 shows a typical wire-wound detector. More details about RTD can be found in "Industrial Temperature Measurement" (Kerlin, 1982).



1. Pt--Wire
2. Glass or Quartz Rod
3. Coating
4. Terminals
5. Ceramic Tube
6. Glazed Sealing

Figure 2.3 Pt-wound resistance temperature detector

2.3 Thermal Model

A: Heat Transfer Theory

Analysis of the complete space-time response of a thermocouple or a RTD requires the solution of appropriate partial differential equations. The partial differential equation that describes transient sensor heat transfer for a medium with constant thermal conductivity is

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{Q}{\rho c}, \tag{2.4}$$

where

T = temperature (^{0}C), (a function of position and time),

t = time (sec.),

α = thermal diffusivity = K/c (m^2/s),

K = thermal conductivity (W/mK),

ρ = density (kg/m^3),

c = specific heat capacity (J/kgK),

Q = heat generation rate (J/s),

∇ = the Laplacian operator.

Nodal analysis, an alternate analytical procedure, involves dividing the solid into sections called nodes, and then calculating the average temperature in each section. This simplifies the analysis considerably, and the results converge to the exact solution as the number of sections increases. Each section is represented by a single temperature called a nodal temperature.

The equation for a section in a one-dimensional nodal heat transfer analysis is

$$\frac{dT_i}{dt}=\frac{Q_i}{MC_i}-\frac{T_i-T_{i-1}}{R_{i-1}(MC)_i}-\frac{T_i-T_{i+1}}{R_{i+1}(MC)_i}\ , \tag{2.5}$$

where

T_i = temperature in node i,

T_{i-1} = temperature in node i-1,

T_{i+1} = temperature in node i+1,

Q_i = heat generation in node i,

M_i = mass of material in node i,

C_i = specific heat capacity of material in node i,

R_{i-1} = heat transfer resistance between nodes i-1 and i,

R_{i+1} = heat transfer resistance between nodes i+1 and i.

The simplest model uses only one node to represent the whole sensor. That is

$$\frac{dT}{dt}=\frac{Q}{MC}-\frac{T-\theta}{RMC}\ , \tag{2.6}$$

where

θ = temperature of the medium that is to be measured.

The thermocouple which was used in DCTS can be approximately described by this simple model. The solution of Equation (2.6) is

$$T(t)=T(\infty)(1-\exp(-t/\tau))\ , \tag{2.7}$$

where

$$\tau = RMC.$$

This is the mathematical model that will be used to describe the dynamic response process of a thermocouple for a step change in temperature input. It is an approximation to the true performance of a thermocouple.

B: Physical Analysis

A simplified sectional drawing of a TC or a RTD and its corresponding thermal model are shown in Figure 2.4.

R1 and C1 represent thermal resistance and capacitance of material used to support the sensing element.

R2 represents thermal resistance of thermal boundary layer of the fluid.

C2 represents a thermal capacitance from contributions to the thermal boundary layer by the fluid, sheath, and material supporting the sensing element.

For a low inertia sensor, the thermal capacitance of the sensor and the thermal resistance of the sheath can be neglected. So, the system can be approximated as a first order system.

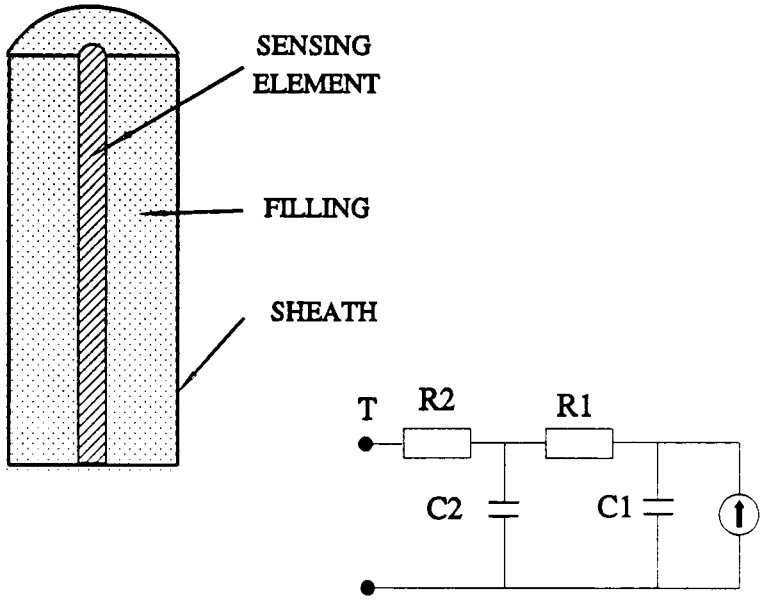


Figure 2.4 Thermal Model of Temperature sensor

2.4 The Dynamic Compensated Temperature Sensor (DCTS)

A: Theoretical Analysis of the DCTS

(a). Introduction

The DCTS design is based on the signal-compensated technique. The signal-compensated method is to use two signals, a fast signal T_f and a slow signal T_s, to form a compensated signal T_C. Each signal has a different time constant. In the Thermal Model Analysis, it was shown that the TC's thermal model can be approximated by a first order system. The theoretical analysis is based on this model. It includes the Laplace domain analysis, the time domain analysis, and fundamental relationships.

(b). Laplace-Domain Analysis

The analysis of the response of temperature sensors is a transient heat transfer problem. This classical problem has been the subject of extensive study, and analytical methods are well-developed. Of the various methods available for calculating transients, two are used much more frequently than the others. One of the most useful methods of attack is based upon the solution of differential equations, with the constants of integration determined from initial conditions. The other procedure of solving the problem is known as the operational method which includes the Fourier integral and

transform and Laplace transformation. In this project, Laplace transforms are used to model the transient.

The transfer functions for the fast sensor signal $T_f(s)$, slow signal $T_s(s)$, and the compensated signal $T_C(s)$ are

$$T_f(s) = \frac{1}{\tau_f s + 1} X(s) \tag{2.8}$$

$$T_s(s) = \frac{1}{\tau_s s + 1} X(s) \tag{2.9}$$

$$T_C(s) = \frac{[k\tau_s - (k-1)\tau_f]s + 1}{(\tau_f s + 1)(\tau_s s + 1)} X(s) \tag{2.10}$$

where

X(s) = temperature signal in the Laplace domain,

τ_f = fast sensor time constant,

τ_s = slow sensor time constant.

Figure 2.5 is the straight line approximation of the Bode magnitude plot of the above transfer functions. The points noted are

A = $1/[\, k\tau_s - (k-1)\tau_f \,]$,

B = $1/\tau_s$ = break frequency of $T_s(j\omega)$,

C = $1/\tau_f$ = break frequency of $T_f(j\omega)$,

D = $1/\tau_c$ = zero magnitude cross frequency of $T_c(j\omega)$.

From Figure 2.5, it can be seen that the band-width of the T_C signal (frequency range between 0 and D) has been expanded. This means that the compensated signal has shorter response

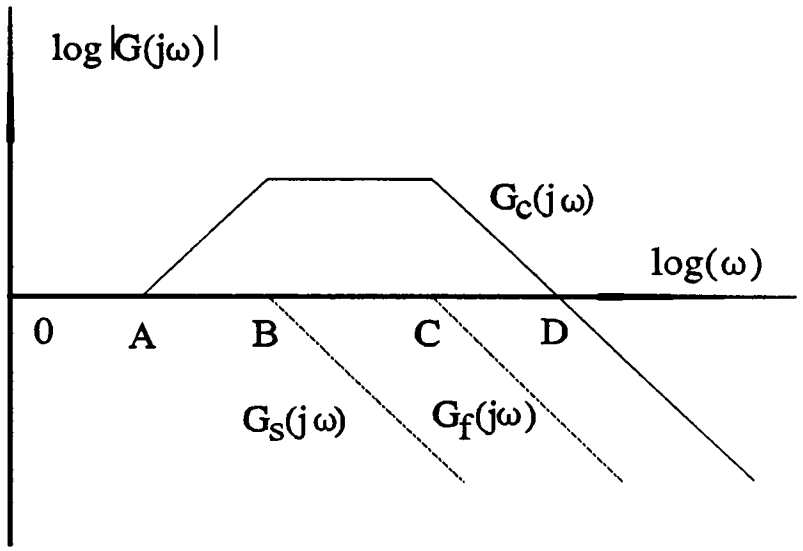


Figure 2.5 DCTS straight line approximation of Bode plot

time than the others.

(c). Time-Domain Analysis

Transient responses of linear dynamic systems are usually judged on the basis of their response to a unit step input and a unit ramp input in the time domain.

In the Laplace domain, when the temperature signal X(s) is a unit step change, the transfer functions of the fast sensor and the DCTS are

$$T_f(s) = \frac{1}{(\tau_f s+1)s} \tag{2.11}$$

$$T_C(s) = \frac{[k\tau_s-(k-1)\tau_f]s+1}{(\tau_f s+1)(\tau_s s+1)s} \tag{2.12}$$

and inverting them to the time-domain, we have

$$T_f(t) = 1-\exp(-t/\tau_f) \tag{2.13}$$

$$T_C(t) = 1 - k\exp(-t/\tau_f) + (k-1)\exp(-t/\tau_s) . \tag{2.14}$$

These are plotted in Figure 2.6.

As time approaches infinity, we obtain the steady-state response of $T_f(t)$ and $T_C(t)$ as

$$\lim_{t\to\infty}[T_f(t)] = 1 \tag{2.15}$$

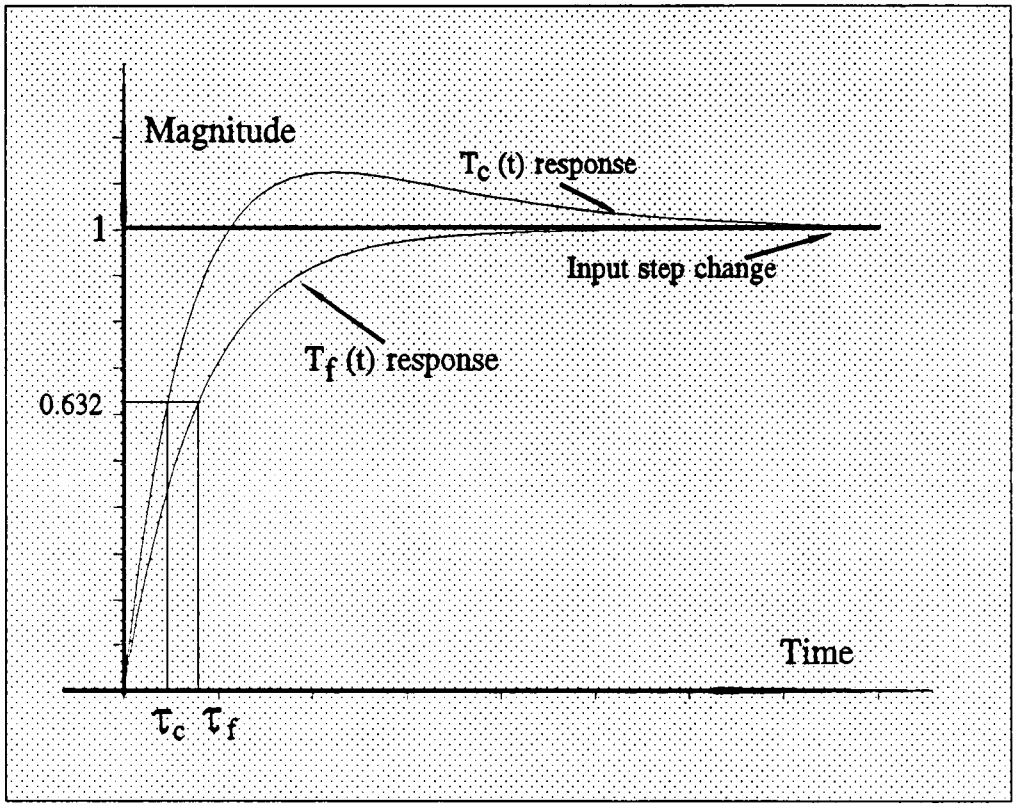


Figure 2.6 DCTS Response to a Unit Step Change

$$\lim_{t\to\infty}[T_c(t)] = 1 \tag{2.16}$$

Therefore both the $T_C(t)$ signal and the $T_f(t)$ signal approach the input signal x(t) in steady state.

According to the definition of the response time constant, from Equation (2.13) and Equation (2.14), we obtain

$$k\exp(-\frac{\tau_c}{\tau_f}) - (k-1)\exp(-\frac{\tau_c}{\tau_s}) = \exp(-\frac{\tau_f}{\tau_f}) \tag{2.17}$$

and since $\tau_s \geq \tau_f$, Equation (2.17) can be written as

$$\exp(-\frac{\tau_c}{\tau_f}) \leq \exp(-\frac{\tau_f}{\tau_f}) \tag{2.18}$$

so

$$\tau_C \leq \tau_f . \tag{2.19}$$

This means the $T_C(t)$ is a faster responding signal than $T_f(t)$.

In the Laplace domain, when the temperature signal X(s) is a unit ramp change, the transfer functions of the fast sensor and the DCTS are

$$T_f(s) = \frac{1}{(\tau_f s+1)s^2} \tag{2.20}$$

$$T_C(s) = \frac{[k\tau_s-(k-1)\tau_f]s+1}{(\tau_f s+1)(\tau_s s+1)s^2} . \tag{2.21}$$

Inverting to the time domain gives

$$T_f(t) = t - \tau_f + \tau_f \exp(-\frac{t}{\tau_f}) \qquad (2.22)$$

$$T_C(t) = t-k\tau_f + (k-1)\tau_S+k\tau_f \exp(-\frac{t}{\tau_f}) - (k-1)\tau_s\exp(-\frac{t}{\tau_s}) . \qquad (2.23)$$

These are plotted in Figure 2.7.

We can define the error e(t) as the difference between the unit ramp input and output response. As time approaches infinity, we obtain the steady-state error function of $T_f(t)$ and $T_C(t)$ as

$$\lim_{t\to\infty}[e_f(t)] = \tau_f \qquad (2.24)$$

$$\lim_{t\to\infty}[e_C(t)] = k\tau_f-(k-1)\tau_S \qquad (2.25)$$

and since $\tau_S \geq \tau_f$, from Equations (2.24), (2.25) we obtain

$$\lim_{t\to\infty}[e_c(t)] \leq \lim_{t\to\infty}[e_f(t)] . \qquad (2.26)$$

This shows that the measurement error between the response of compensated signal and the ramp temperature input is smaller than that of fast signal at steady state.

(d). Fundamental Relationships

Figure 2.6 has shown the response of the fast and compensated signals to a step change in temperature. As expected, τ_C is smaller than τ_f. However, an overshoot is

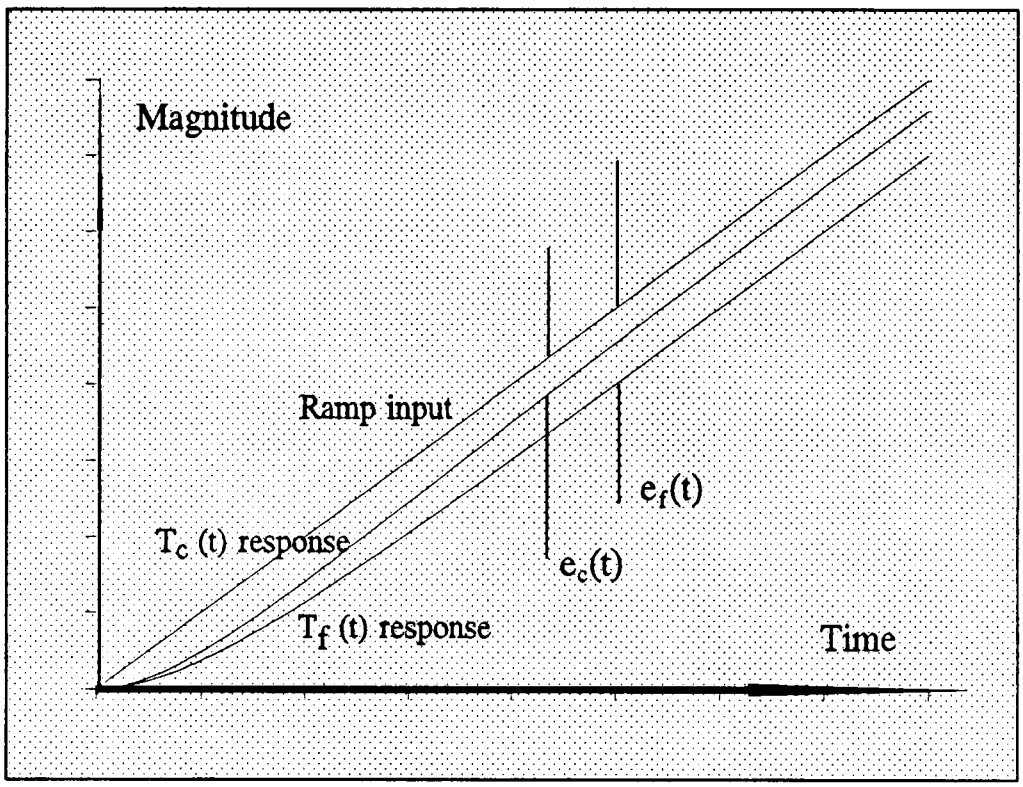


Figure 2.7 DCTS Response to a Unit Ramp Change

created in the compensated signal.

The DCTS design requirements are small response time constant and minimal overshoot. They are determined by the parameters k, τ_s and τ_f. The following analysis studies the relationships between the DCTS parameters for a step change in external temperature. In order to judge the response of Tc(t), some parameters are defined:

max{Tc} = maximum value of Tc(t),

overshoot = max(Tc) - 1,

τ_c = time constant of Tc(t),

m = τ_s/τ_f,

a = τ_c/τ_f ,

b = fractional improvement in τ_f=(τ_f - τ_c)/τ_f=1 - a.

These parameters are shown in Figure 2.8.

(1). The relationship between k, m (τ_s/τ_f), and max{Tc}

In order to find the maximum value of $T_C(t)$, from Equation (2.14), we can obtain the derivative of $T_C(t)$ with respect to time as

$$\frac{d}{dt}[T_C(t)] = \frac{k}{\tau_f}\times\exp(-\frac{t}{\tau_f})-\frac{k-1}{\tau_s}\times\exp(-\frac{t}{\tau_s}) \qquad (2.27)$$

When the left side of Equation (2.27) is zero, we have

$$\frac{(k-1)\tau_f}{k\tau_s} = \frac{\exp(-t/\tau_f)}{\exp(-t/\tau_s)}$$

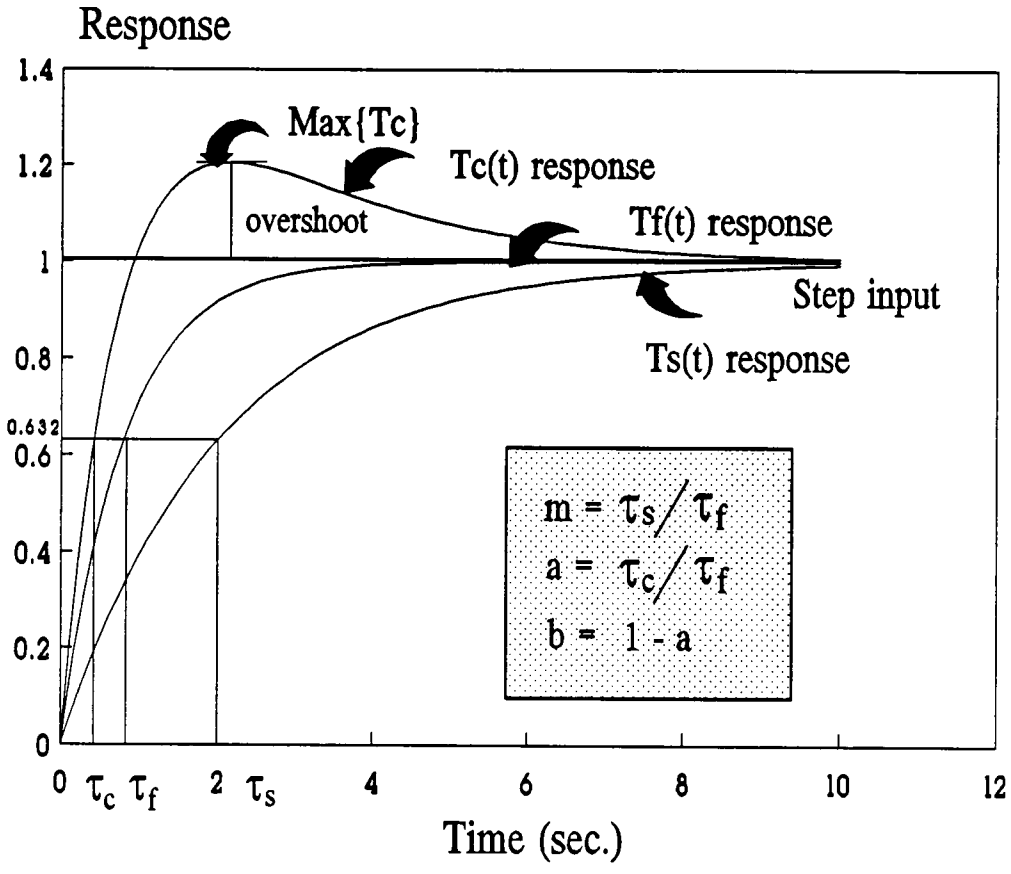


Figure 2.8 Signals from DCTS

$$\ln\frac{(k-1)\tau_f}{k\tau_s} = \frac{t}{\tau_s} - \frac{t}{\tau_f}$$

So

$$t = \frac{\tau_s\tau_f}{\tau_f-\tau_s}\ln\frac{(k-1)\tau_f}{k\tau_s} . \qquad (2.28)$$

Substituting Equation (2.28) into Equation (2.27) and using $m=\tau_s/\tau_f$, we obtain the relationship for max{Tc}:

$$\max(Tc) = (k-1)\exp(\frac{\ln(k-1)/km}{m-1}) - k\times\exp(\frac{mln[(k-1)/km]}{m-1})+1 . \qquad (2.29)$$

As m approaches infinity (τ_f approaches zero)

$$\lim_{m\to\infty}(\max[Tc]) = k . \qquad (2.30)$$

Figure 2.9 shows the relation between m and max{Tc} when k = 2. Figure 2.10 shows the relation between k and max{Tc} when m = 4.

From Equations (2.29), (2.30), Figures 2.9, 2.10, it can be seen that

(1) max{Tc} is determined by k and m.

(2) When m increases, max{Tc} increases as well. This can be seen in Figure 2.9.

(3) When m approaches infinity, max{Tc} = k.

(4) When k increases, max{Tc} increases as shown in Figure 2.10.

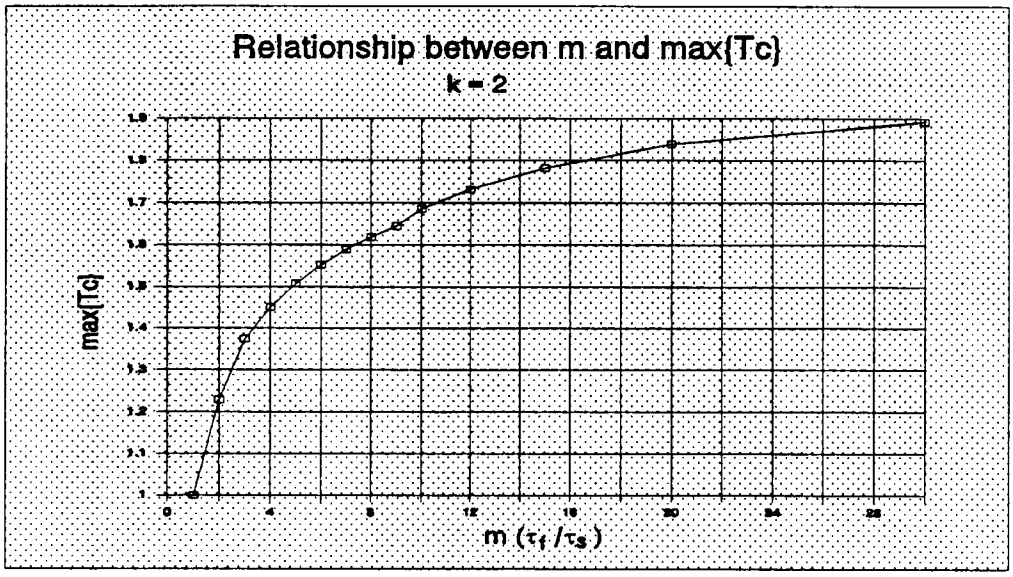


Figure 2.9 Relationship between m and max{Tc}

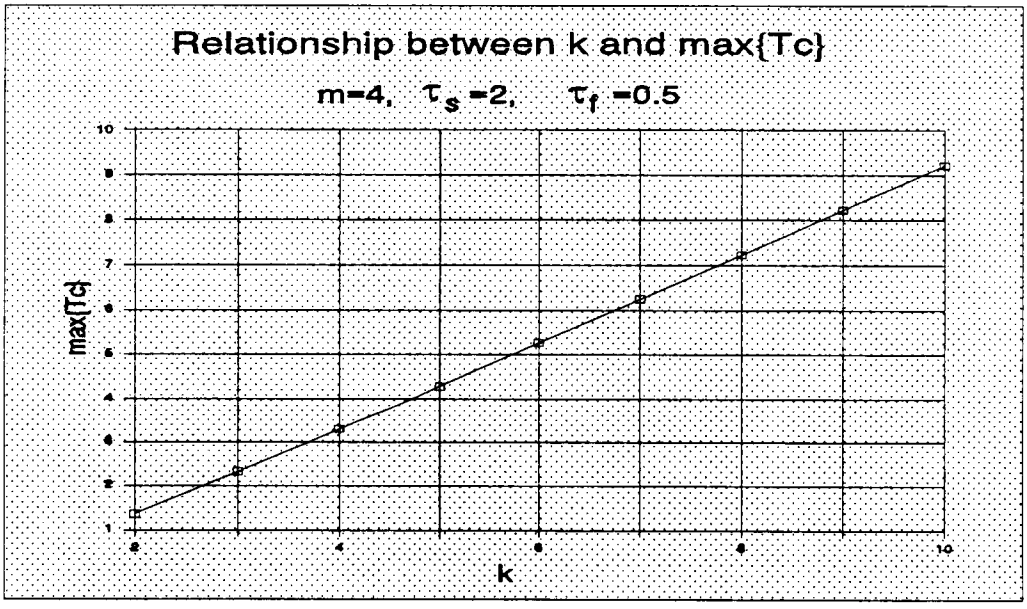


Figure 2.10 Relationship between k and max{Tc}

(2). The relationship between k, m(τ_s/τ_f), and a

According to the definition of the time constant and m, from Equation (2.14) the relation for a as a function of k can be developed

$$0.632 = 1 - e^{-a/m} + k(e^{-a/m} - e^{-a}) \tag{2.31}$$

when m approaches infinity

$$a = \ln\frac{k}{k-0.632} . \tag{2.32}$$

Equation (2.31) does not show a direct relation between a and m, or a and k. So, a Fortran program DCTS.FOR was written to calculate the values of a, m, k and max{Tc} based on Equations (2.29) and (2.31). This program is given in Appendix 1. Table 2.1 lists the values of a corresponding to different values of m. Table 2.2 lists the values of a and max{Tc} corresponding to different values of k. These values were generated by the program DCTS.FOR.

Figure 2.11 shows the relation between m and a based on Table 2.1. Figure 2.12 shows the relation between k and a based on Table 2.2.

From Equation (2.31), Equation (2.32), Figure 2.11, and Figure 2.12, we can see that

(1) a is determined by k and m.

(2) When m increases, τ_c decreases nonlinearly. When k is constant, m tends to infinity, and τ_c will be a

Table 2.1. The values of a corresponding to m (DCTS)

k = 2			τ_f = 0.1
τ_s	m (τ_s/τ_f)	τ_C	a (τ_C/τ_f)
0.1	1.0	0.1	1.0
0.2	2.0	0.06	0.6
0.3	3.0	0.05	0.5
0.4	4.0	0.047	0.47
0.5	5.0	0.045	0.45
0.6	6.0	0.044	0.44
0.7	7.0	0.043	0.43
0.8	8.0	0.042	0.42
0.9	9.0	0.041	0.41
1.0	10.0	0.0405	0.405
1.2	12.0	0.0402	0.402
1.5	15.0	0.040	0.40
2.0	20.0	0.039	0.39
3.0	30.0	0.0385	0.385

Table 2.2 The values of a and max{Tc} corresponding to k

τ_f = 0.5		τ_s = 2	m = 4
k	τ_C	a	max{Tc}
2	0.23	0.46	1.37499
3	0.13	0.26	2.32759
4	0.09	0.18	3.29764
5	0.07	0.14	4.27630
6	0.06	0.12	5.26001
7	0.05	0.10	6.24699
8	0.045	0.09	7.23624
9	0.038	0.076	8.22714
10	0.035	0.07	9.21930

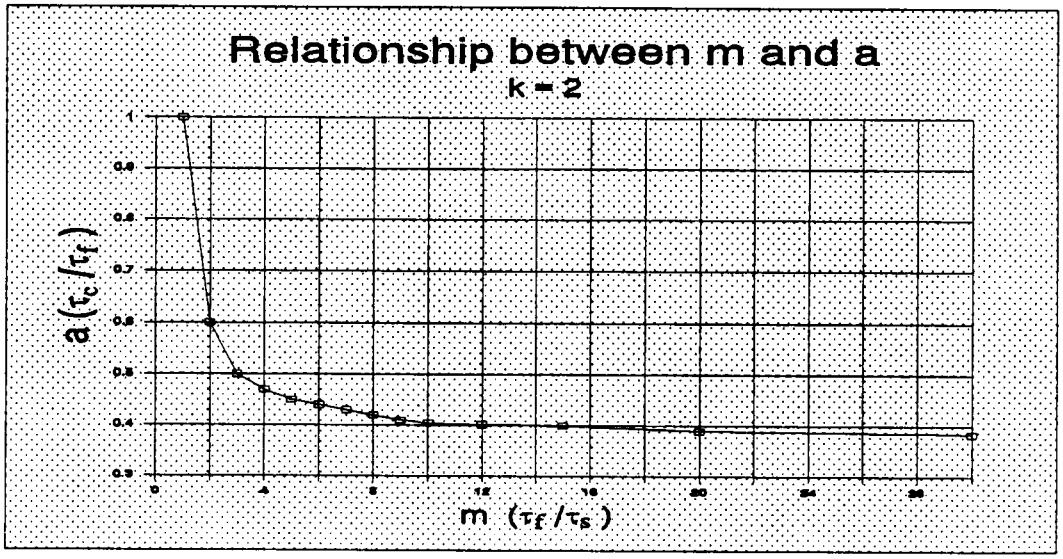


Figure 2.11 Relationship between m and a

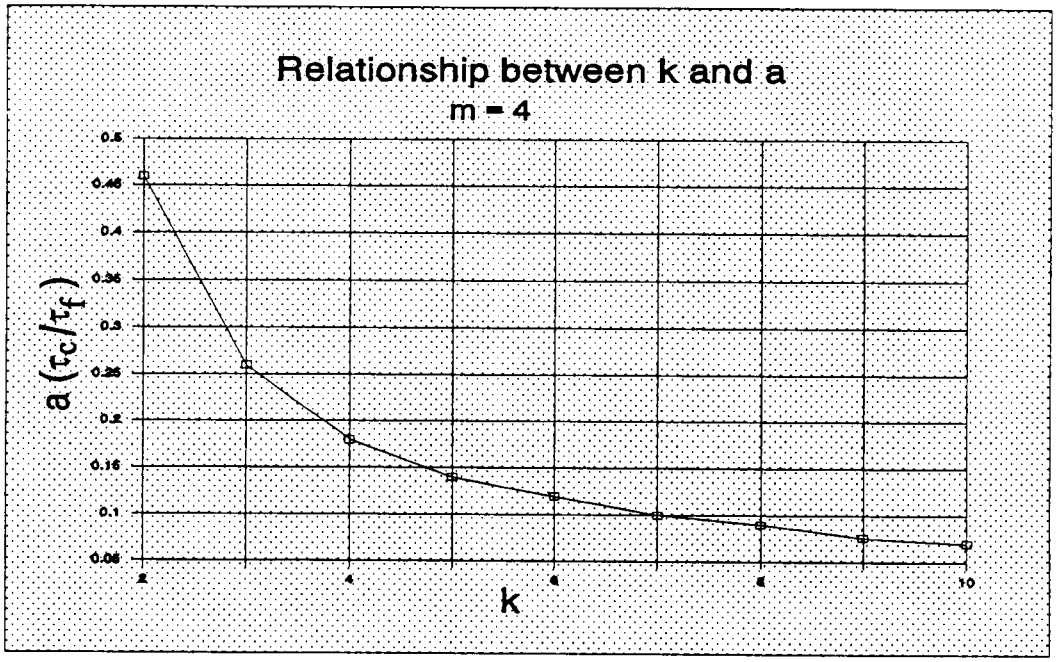


Figure 2.12 Relationship between k and a

fixed value. We can see this in Figure 2.11.

(3) When k increases, τ_c decreases.

(3). Relationship between the overshoot and improvement of the time constant

From Equation (2.31), we can obtain

$$m = -\frac{a}{A}, \tag{2.33}$$

where

$$A = \ln\frac{k\,e^{-a} - 0.368}{k-1}.$$

Substitute Equation (2.33) into (2.29) to obtain

$$\max(Tc) = \left[\frac{A(1-k)}{a}\right]^{\frac{a}{a+A}} \times k^{\frac{A}{a+A}} \times \left(-\frac{a+A}{A}\right) + 1. \tag{2.34}$$

Using the definitions of overshoot and b, Equation (2.34) can be rewritten as

$$overshoot = \left[\frac{A(1-k)}{1-b}\right]^{\frac{1-b}{1+A-b}} \times k^{\frac{A}{1+A-b}} \times \left(-\frac{1+A-b}{A}\right). \tag{2.35}$$

Figure 2.13 shows the relationship between overshoot and improvement in τ_f based on Equation (2.35). From Fig. 2.13, we can see

(1) for the same improvement, when k increases, overshoot decreases, and

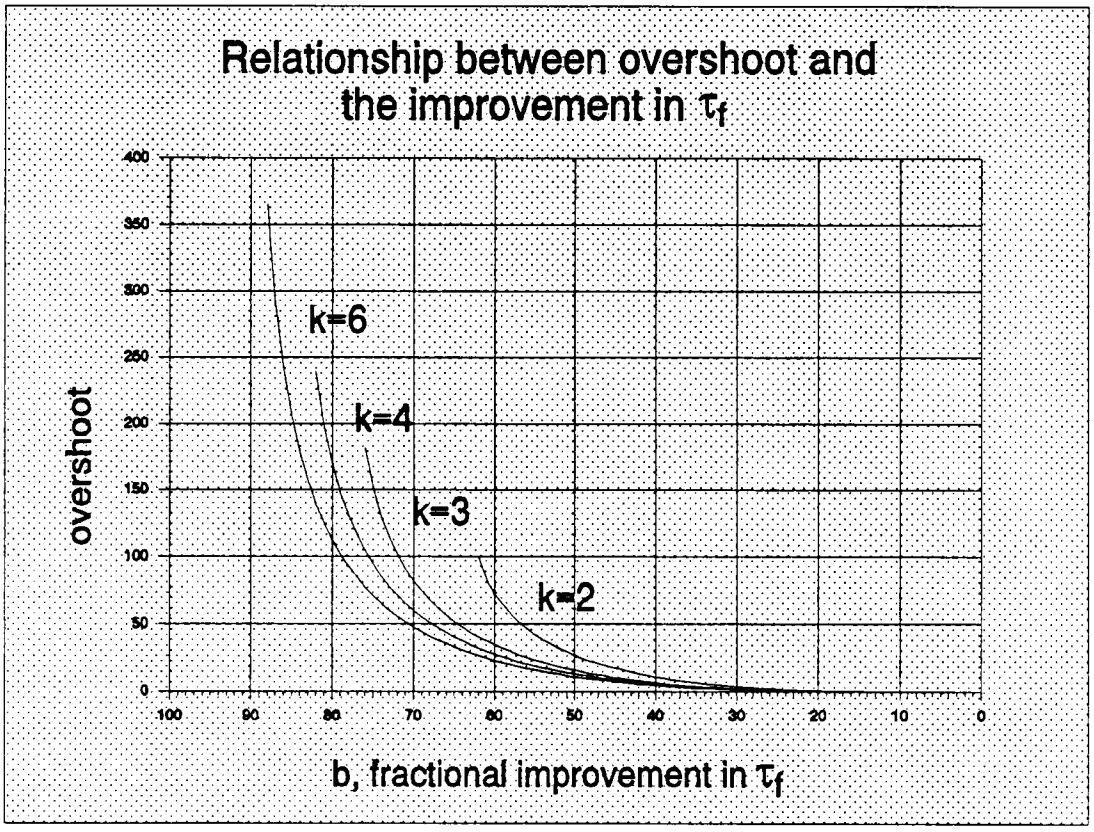


Figure 2.13 Relationship between overshoot and the improvement in τ_f

(2) when k increases, the improvement and overshoot will increase too, but for a fixed k, the improvement and overshoot will tend to fixed values.

B: Design Using Two Independent Signals

(a). Introduction

The basic idea of the DCTS is to use two signals, a fastsignal T_f and a slow signal T_s, to form a compensated signal T_c. Each signal has a different response time constant. We can use the ordinary temperature sensor's output as the fast signal. The slow signal can be generated in different ways. The simplest way is to use two independent signals. This can be accomplished by placing two sensing elements in the same sheath, one is near the tip and one higher in the sheath. We call this kind of sensor the Dynamic Compensated Temperature Sensor with Independent Signals (DCI). Figure 2.14 shows the construction of DCI. This method is the first one to be evaluated.

Since the DCI uses two independent signals as the fast and slow signals, it has the same behavior as the DCTS that we described before. All the relationships in DCI are same as that in the DCTS.

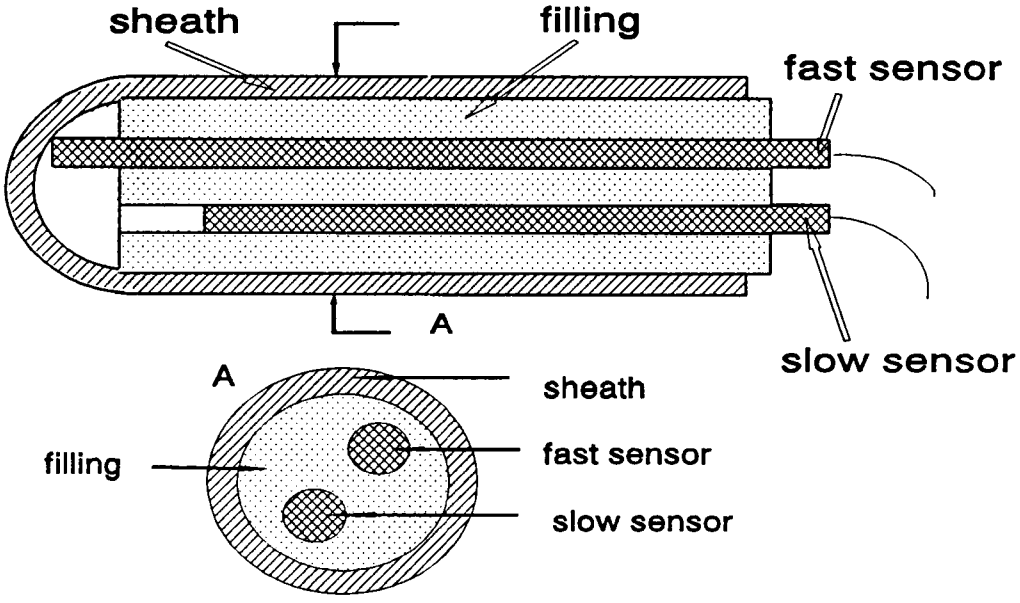


Figure 2.14 Construction of DCI

(b). DCI Design

The relationships between $T_C(t)$ and $T_s(t)$, $T_f(t)$ have been described. How to find a good T_C is dependent on finding the proper k, τ_s, and τ_f. This work can be done by a computer.

A general purpose computer program for finding the proper parameters in the design of DCI has been developed. The program, called DCI.FOR, permits dynamic simulation of DCI. It is written in the FORTRAN computer language.

Ordinarily, we want the compensated signal $T_C(t)$ to have a small time constant and a small max{Tc}. So, based on the basic relationships of DCI, parameters k and m should not be very large. DCI.FOR restricted the range of k and m as follows: k is greater than 2 but less than 10, and m is greater than 2 but less than 30. The input requirements by the program are as follows:

A. $\max\{\tau_c\}$, which is the largest value of τ_c that we can tolerate,

B. $\max\max\{T_C\}$, which is the largest value of $\max\{T_C\}$ that we can tolerate, and

C. τ_f, which is the time constant of the ordinary temperature sensor used as the fast sensor in DCI.

When these limits are input to the program it outputs the ranges of k and m that can meet the requirements and the corresponding values of τ_c and max{Tc}.

The program DCI.FOR is given in Appendix 2.

C: Design Using Lagged Signals

(a). Introduction

Using a lagged signal to increase response time is a newly developed method for the Dynamic Compensated Temperature Sensor Design. We call it the Dynamic Compensated Temperature Sensor with Lagged Signal (DCL). DCL is based on using the original sensor output signal $T_f(t)$, to form a lagged signal $T_L(t)$. The enhanced response is achieved by using the signal

$$T_c(t) = k \times T_f - (k-1) \times T_L \tag{2.36}$$

where

$Tc(t)$ = compensated temperature signal,

$T_f(t)$ = fast sensor output signal,

$T_L(t)$ = lagged signal from $T_f(t)$,

k = a constant.

This system is shown schematically in Figure 2.15.

Since the DCL uses a different slow signal, its compensated signal model is different from that of the DCTS. A new theoretical analysis is needed to study the behavior of the DCL.

(b). Laplace Domain Analysis

The transfer functions for the original sensor signal $T_f(s)$, lagged signal $T_L(s)$, and the compensated signal $T_c(s)$

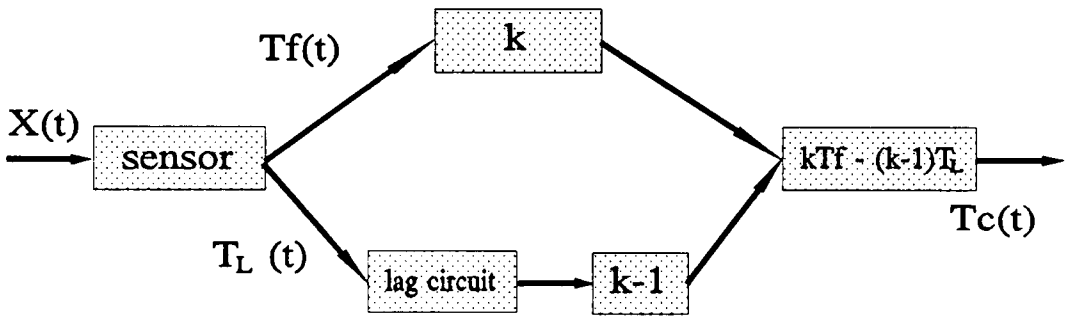


Figure 2.15 The DCL System

are

$$T_f(s) = \frac{1}{\tau_f s+1} X(s) \tag{2.37}$$

$$T_L(s) = \frac{1}{Ls+1} T_f(S) \tag{2.38}$$

$$T_C(s) = \frac{kLs+1}{(\tau_f s+1)(Ls+1)} X(s) \tag{2.39}$$

where

X(s) = input temperature signal in the Laplace domain,

τ_f = original sensor response time constant,

L = lag time constant.

Figure 2.16 shows the straight line approximation of the Bode plots of the fast signal and compensated signal for $L<(\tau_f/k)$, $L=(\tau_f/k)$, and $L>(\tau_f/k)$. It can be seen that the band-width of the T_C signal has been expanded in all cases. This means the compensated signal has a shorter response time constant than that of the original signal T_f. The Bode plot also shows that when $L\leq(\tau_f/k)$, the gain of the compensated signal is never higher than the gain of the fast signal. This indicates that the compensated signal has no overshoot. This is an advantage of using lagged signal over using two independent signals.

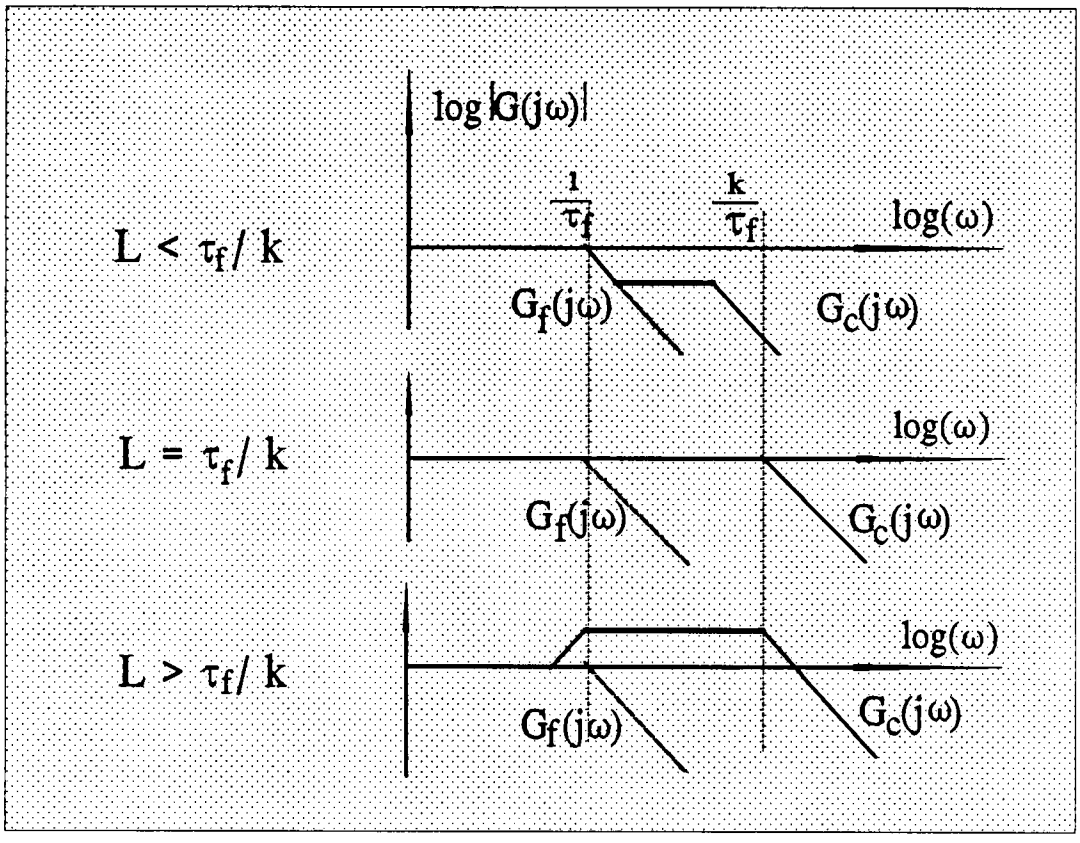


Figure 2.16 DCL Straight Line Approximation of the Bode Plot

(c). Time-Domain Analysis

In the time-domain, the response of the original sensor and the DCL to a unit step temperature change is

$$T_f(t) = 1-\exp(-t/\tau_f) . \tag{2.40}$$

When $L \neq \tau_f$

$$T_c(t) = 1 - \frac{kL-\tau_f}{L-\tau_f}\exp(-\frac{t}{\tau_f}) + \frac{(k-1)L}{L-\tau_f}\exp(-\frac{t}{L}) , \tag{2.41}$$

and when $L=\tau_f$

$$T_c(t) = 1 - \exp(-\frac{t}{\tau_f}) + \frac{(k-1)t}{\tau_f}\exp(-\frac{t}{\tau_f}) . \tag{2.42}$$

As time approaches infinity, we obtain the steady state values of $T_f(t)$ and $T_C(t)$ as

$$\lim_{t\to\infty}[T_f(t)] = 1 \tag{2.43}$$

$$\lim_{t\to\infty}[T_c(t)] = 1 . \tag{2.44}$$

This shows that both the $T_C(t)$ signal and the $T_f(t)$ signal approach the input signal x(t) in steady state.

According to the definition of the response time constant, from Equation (2.40) and Equation (2.41), we can obtain

$$\frac{kL-\tau_f}{L-\tau_f}\exp(-\frac{\tau_c}{\tau_f}) + \frac{(k-1)L}{L-\tau_f}\exp(-\frac{\tau_c}{L}) = \exp(-\frac{\tau_f}{\tau_f}) . \quad (2.45)$$

In equation (2.45) if $L \neq \tau_f$, then

$$\frac{kL-\tau_f}{L-\tau_f}\exp(-\frac{\tau_c}{\tau_f}) + \frac{(k-1)L}{L-\tau_f}\exp(-\frac{\tau_c}{L}) < \exp(-\frac{\tau_c}{\tau_f})$$

and

$$\exp(-\frac{\tau_f}{\tau_f}) < \exp(-\frac{\tau_c}{\tau_f})$$

so

$$\tau_c < \tau_f . \quad (2.46)$$

If $L=\tau_f$, we get the same result.

The response of the original sensor and the DCL to a ramp temperature change are

$$T_f(t) = t - \tau_f + \tau_f \exp(-\frac{t}{\tau_f}) . \quad (2.47)$$

When $L \neq \tau_f$

$$T_c(t) = \frac{kL-\tau_f}{L-\tau_f}(t-\tau_f + \tau_f e^{-t/\tau_f}) - \frac{(k-1)L^2}{L-\tau_f}(t-L+Le^{-t/L}) \quad (2.48)$$

and when $L=\tau_f$

$$T_c(t) = t+(k-2)\tau_f [1-\exp(-\frac{t}{\tau_f})]-(k-1)t \exp(-\frac{t}{\tau_f}) . \quad (2.49)$$

As time approaches infinity, the error of the fast signal $e_f(t)$

is

$$\lim_{t\to\infty}[e_f(t)] = \tau_f \tag{2.50}$$

When $L \neq \tau_f$, the error of the compensated signal $e_c(t)$ is

$$\lim_{t\to\infty}[e_c(t)] = \tau_f - (k-1)L \tag{2.51}$$

and when $L=\tau_f$

$$\lim_{t\to\infty}[e_c(t)] = \tau_f - (k-1)\tau_f \tag{2.52}$$

comparing Equation (2.50) with Equations (2.51) and (2.52), we obtain

$$\lim_{t\to\infty}[e_c(t)] < \lim_{t\to\infty}[e_f(t)] \tag{2.53}$$

In the above analysis, we have shown that the DCL can improve the temperature sensor's response speed, and that there is no overshoot when $L \leq \tau_f/k$.

(d). DCL Response to an Arbitrary Temperature Change

In the real world, we don't always have step or ramp temperature changes. In most cases, temperature will change randomly. An arbitrary temperature signal, x(t), can be approximated by the sum of n time-displaced temperature steps, which form the staircase function shown in Figure 2.17.

This staircase function consists of an initial rise at

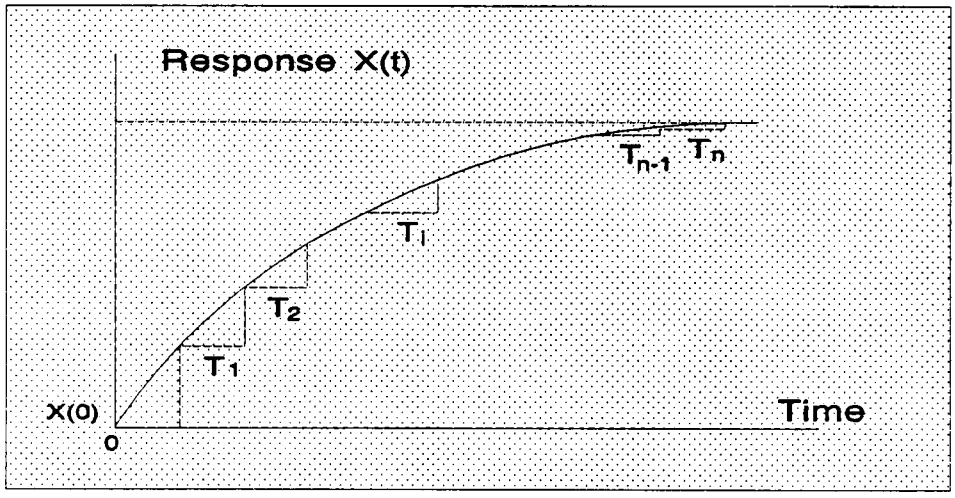


Figure 2.17 Illustration of method of superposition

t=0, plus the sum of n finite steps occurring at equal time intervals of T. The general temperature step can be expressed as U(t-iT), and the approximate expression for x(t) is

$$x(t) \cong x(0)U(t)+\sum_{i=1}^{n} \Delta a_i U(t-iT) \tag{2.54}$$

where

$n = t/T,$

$\Delta a_i = x(iT) - x((i-1)T),$

$U(t)$ = unit step change.

The response to the staircase function can be found by applying the superposition theorem.

In the Laplace domain, the staircase function of the temperature signal can be written as

$$X(s) = \sum_{i=1}^{n} \Delta a_i \frac{e^{-isT}}{s} \tag{2.55}$$

So

$$T_f(s) = \sum_{i=1}^{n} \Delta a_i [\frac{e^{-isT}}{s} - \frac{e^{-isT}}{s+1/\tau_f}] \tag{2.56}$$

$$\begin{aligned} T_c(s) = & \frac{\tau_f - kL}{\tau_f - L} \sum_{i=1}^{n} \Delta a_i [\frac{e^{-isT}}{s} - \frac{e^{-isT}}{s+1/\tau_f}] \\ & + \frac{(k-1)L}{\tau_f - L} \sum_{i=1}^{n} \Delta a_i [\frac{e^{-isT}}{s} - \frac{e^{-isT}}{s+1/L}] \end{aligned} \tag{2.57}$$

Inverting $T_f(s)$ and $T_C(s)$ to the time-domain,

$$T_f(t) = x(t) - \sum_{i=1}^{n} \Delta a_i e^{-(t-iT)/\tau_f} U(t-iT) \tag{2.58}$$

$$\begin{aligned} T_c(t) = {} & \frac{\tau_f - kL}{\tau_f - L} \sum_{i=1}^{n} \Delta a_i U(t-iT)[1 - e^{-(t-iT)/\tau_f}] \\ & + \frac{(k-1)L}{\tau_f - L} \sum_{i=1}^{n} \Delta a_i U(t-iT)[1 - e^{-(t-iT)/L}] \end{aligned} \tag{2.59}$$

Similarly, if $T_f(t)$ is considered as a staircase function, then $T_C(t)$ can be written as

$$T_c(iT) = (T_c[(i-1)T] - T_f[(i-1)T])e^{-T/L} + T_f(iT) + (k-1)\Delta b_i \tag{2.60}$$

where

$$\Delta b_i = T_f(iT) - T_f((i-1)T).$$

Equation (2.60) shows the relationships between $T_C((i-1)T)$, $T_f((i-1)T)$ and $T_C(iT)$. It is used to form the computer simulated $T_C(t)$ signal.

(e). Fundamental Relationships

The DCL design requirements are small response time constant and minimal overshoot. They are both determined by the parameters k and L. The following analysis studies the relationships between these DCL parameters for step change in temperature. In order to judge the response of $T_C(t)$, some parameters are defined:

max{Tc} = maximum value of $T_C(t)$,

τ_c = time constant of $T_C(t)$,

m = L/τ_f,

a = τ_c/τ_f.

(1). The relationship between k, m(L/τ_f), and max{Tc}

According to the definitions of m and a, Equation (2.41) can be written

$$T_c(t) = 1-\frac{km-1}{m-1}e^{-t/\tau_f}+\frac{(k-1)m}{m-1}e^{-t/m\tau_f} \quad . \tag{2.61}$$

In order to find the maximum value of $T_C(t)$, we can obtain the derivative of $T_C(t)$ from Equation (2.61) as

$$\frac{d}{dt}[T_C(t)] = \frac{km-1}{(m-1)\tau_f}e^{-t/\tau_f} - \frac{k-1}{(m-1)\tau_f}e^{-t/m\tau_f} \quad . \tag{2.62}$$

Let the left side of Equation (2.62) be zero, we have

$$(km-1)e^{-t/\tau_f} = (k-1)e^{-t/m\tau_f}$$

$$[e^{-t/\tau_f}]^{(m-1)/m} = \frac{k-1}{km-1}$$

so that

$$e^{-t/\tau_f} = [\frac{k-1}{km-1}]^{m/(m-1)} \tag{2.63}$$

$$e^{-t/m\tau_f} = [\frac{k-1}{km-1}]^{1/(m-1)} \quad . \tag{2.64}$$

Substituting Equations (2.63) and (2.64) into Equation (2.62),

we obtain the formula for max{Tc} as

$$\max(Tc) = 1 - (k-1)\exp(-k/(k-1)), \quad m = 1. \tag{2.65}$$

For m ≠ 1

$$\max(Tc) = 1 + [\frac{(k-1)^m}{km-1}]^{\frac{1}{m-1}}. \tag{2.66}$$

Figure 2.18 shows the relationship between m and max{Tc} when k is 2. Figure 2.19 shows the relation between k and max{Tc} when m is 4.

From Equations (2.65) and (2.66), Figure 2.18, 2.19, it can be seen that

(1) max{Tc} is determined by k and m ($m=L/\tau_f$),

(2) When the product k×m is equal to or smaller than 1, there is no overshoot

(3) When m increases, max{Tc} increases as well. This can be seen in Figure 2.18

(4) When k increases, max{Tc} increases as shown in Figure 2.19.

(2). The relationship between k, L, τ_f and a

According to the definition of the time constant and m, from Equations (2.41) and (2.42), we find the equations for $a(L/\tau_f)$ to be

$$0.632 = 1 - e^{-a} + (k-1)ae^{-a}, \quad m = 1. \tag{2.67}$$

For m ≠ 1

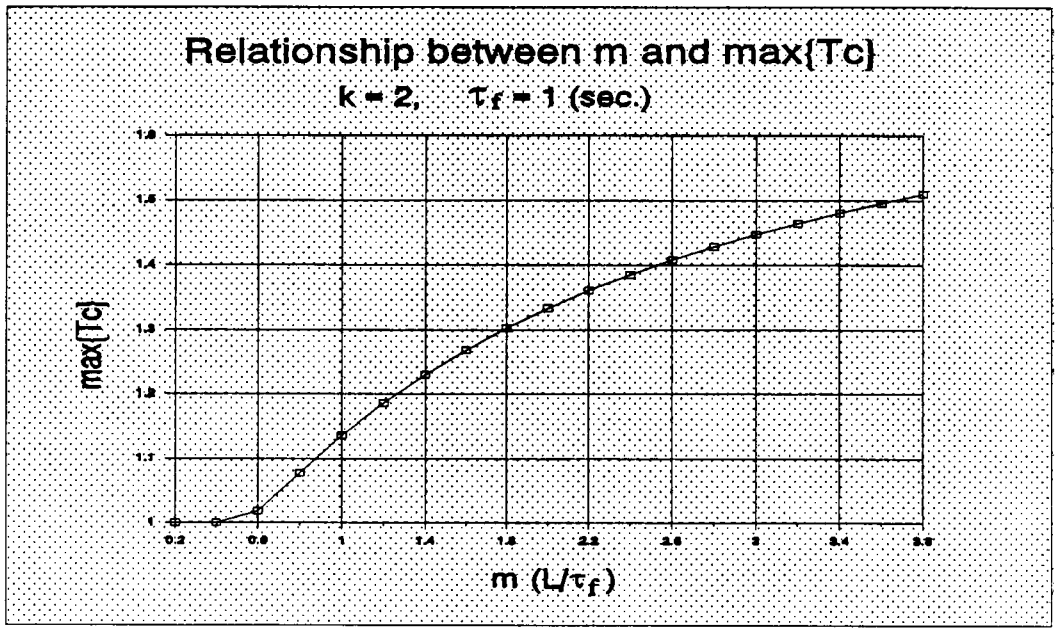


Figure 2.18 Relationship between m and max{Tc}

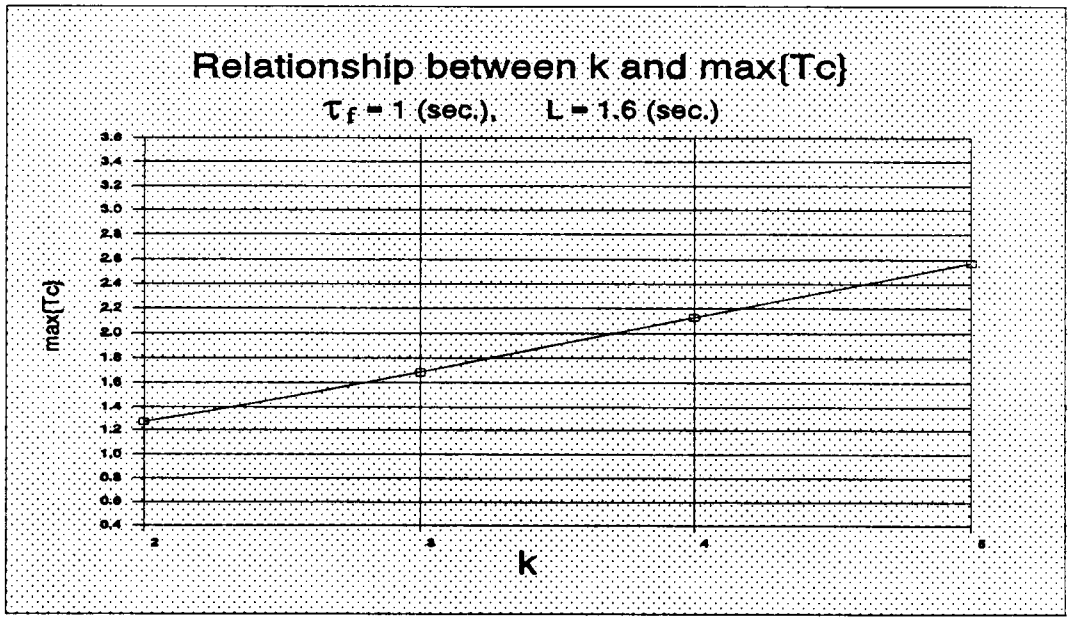


Figure 2.19 Relationship between k and max{Tc}

$$0.632 = 1 - \frac{km-1}{m-1}e^{-a} + \frac{(k-1)m}{m-1}e^{-a/m} . \qquad (2.68)$$

When m approaches infinity (τ_f approaches zero)

$$\lim_{m\to\infty}(a) = \ln\frac{k}{k-0.632} . \qquad (2.69)$$

Equations (2.67) and (2.68) do not show a direct relationship between a and m or between a and k. So, a FORTRAN program DCL.FOR was developed to calculate the values of a, m, k and max{Tc} based on Equations (2.65), (2.66), (2.67), and (2.68). This program is given in Appendix 3. Table 2.3 lists the values of a and max{Tc} corresponding to m when k is 2. Table 2.4 lists the values of a and max{Tc} corresponding to k. Table 2.5 lists the values of a and max{Tc} corresponding to m when k is 5. The values in these tables were generated by the program DCL.FOR.

Figure 2.20 shows the relationship between m and a based on Table 2.4. Figure 2.21 shows the relationship between k and a based on Table 2.4.

From Equations (2.67), (2.68), and (2.69) and Tables 2.5 and 2.5, we can see that

(1) a is determined by k and m.

(2) When m increases, τ_c decreases nonlinearly. (When k is constant, m tends to infinity, and τ_c will be a fixed value). We can see this in Table 2.5 and Figure 2.20.

Table 2.3 The values of a, max{Tc} corresponding to m (DCL, k=2)

k = 2			τ_f = 1
L	m (L/τ_f)	max{Tc}	a (τ_C/τ_f)
0.2	0.2	1	0.72998
0.4	0.4	1	0.53857
0.6	0.6	1.01789	0.47583
0.8	0.8	1.07776	0.44812
1.0	1.0	1.13534	0.43274
1.2	1.2	1.18593	0.42297
1.4	1.4	1.23005	0.41626
1.6	1.6	1.26872	0.41138
1.8	1.8	1.30289	0.40759
2.0	2.0	1.33333	0.40466
2.2	2.2	1.36066	0.40222
2.4	2.4	1.38536	0.40027
2.6	2.6	1.40782	0.39868
2.8	2.8	1.42835	0.39772
3.0	3.0	1.44721	0.39600
3.2	3.2	1.46462	0.39502
3.4	3.4	1.48073	0.39404
3.6	3.6	1.49572	0.39319
3.8	3.8	1.50969	0.39246
4.0	4.0	1.52276	0.39185

Table 2.4 The values of a and max{Tc} corresponding to k (DCL)

τ_f = 1		L = 1.6	a = 1.6
k	τ_C	a	max{Tc}
2	0.41138	0.41138	1.26872
3	0.25122	0.25122	1.68618
4	0.18024	0.18024	2.12633
5	0.14038	0.14038	2.57397

Table 2.5 The values of a and max{Tc} corresponding to m (DCL, k=5)

k	$m(L/\tau_f)$	max{Tc}	$a(\tau_c/\tau_f)$
5	0.5	1.5625	0.15393
5	1.0	2.14602	0.15380
5	1.5	2.51479	0.14075
5	2.0	2.77778	0.13928
5	2.5	2.97834	0.13843
5	3.0	3.13809	0.13788
5	3.5	3.26929	0.13745
5	4.0	3.37955	0.13718
5	4.5	3.47389	0.13696
5	5.0	3.55577	0.13675

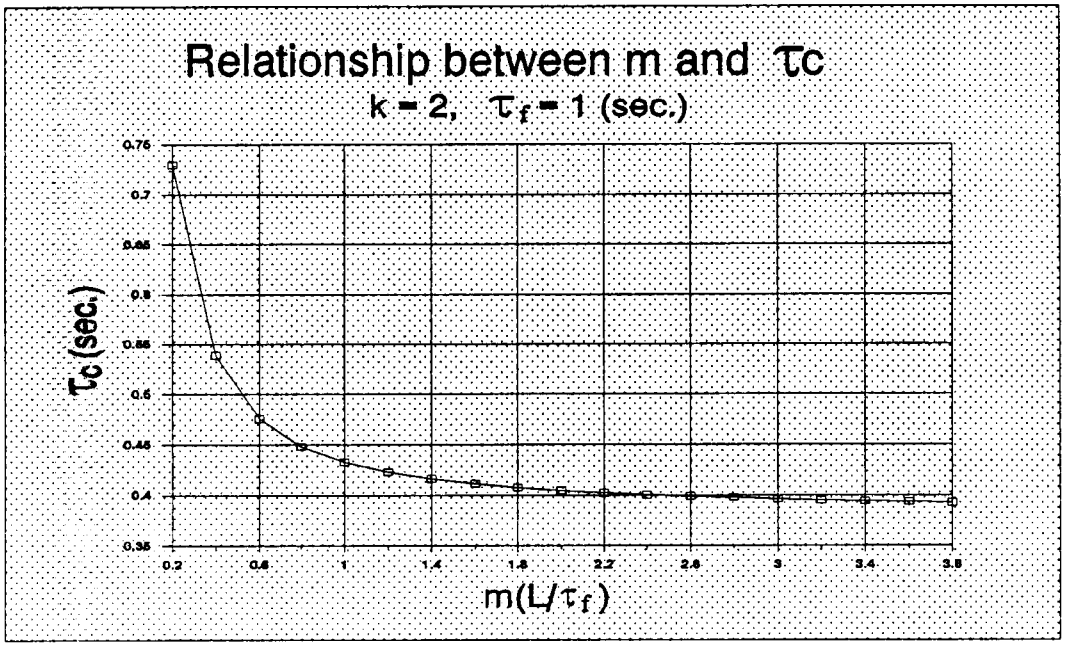


Figure 2.20 Relationship between m and τ_c

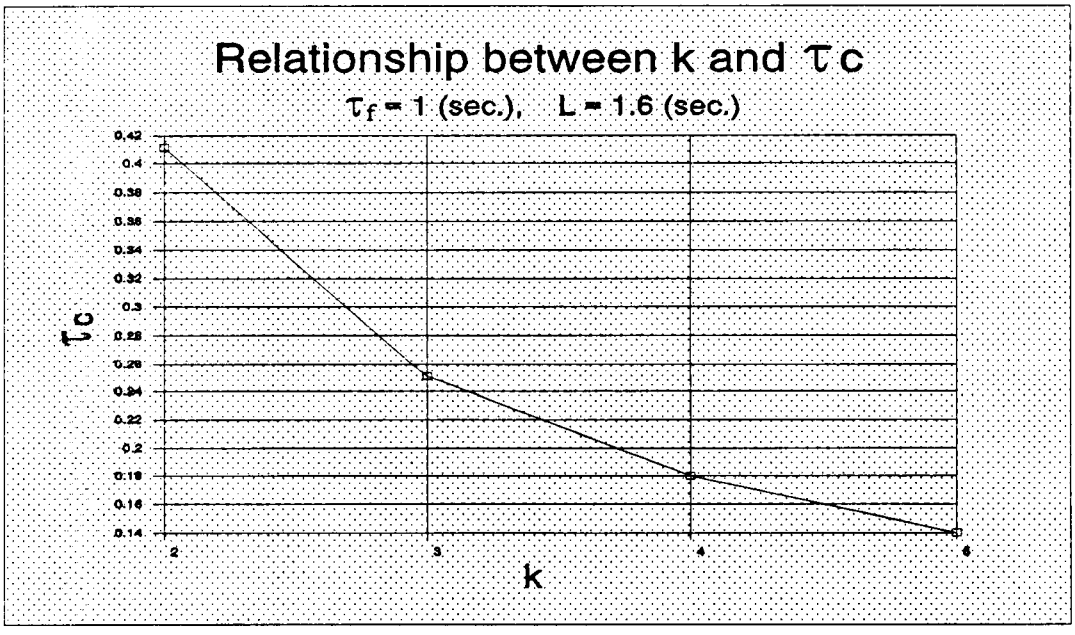


Figure 2.21 Relationship between k and τ_c

(3) When k increases, τ_c decreases as indicated by Table 2.4 and Figure 2.21.

(3). The relationship between max{Tc} and a

Figure 2.22 shows the relationship between a and max{Tc} when k is 2. Figure 2.23 shows the relation between a and max{Tc} when k is 5. These figures are based on Tables 2.3 and 2.6.

From Tables 2.3 and 2.5 and Figures 2.22 and 2.23, we can see that

(1) When k is constant, τ_c/τ_f increases and max{Tc} will decrease (see Figure 2.22).

(2) For fixed a (τ_c/τ_f), when k increases, max{Tc} will decrease.

(f). Special Point

From the basic relationships analysis, we can see that when m = 1/k, the compensated signal has no overshoot and its time constant is the smallest possible under the no overshoot condition.

For this special condition, the transfer function is

$$T_c(s) = \frac{1}{\frac{\tau_f s}{k}+1} . \qquad (2.70)$$

This equation shows that $T_C(t)$ becomes a first order system

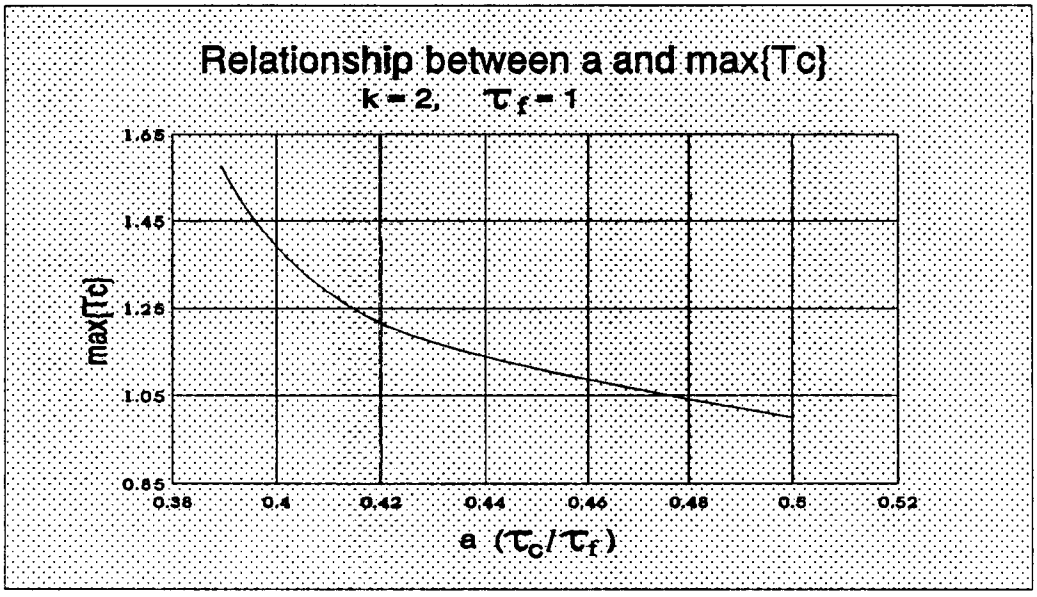


Figure 2.22 Relationship between a and max{Tc} (k=2)

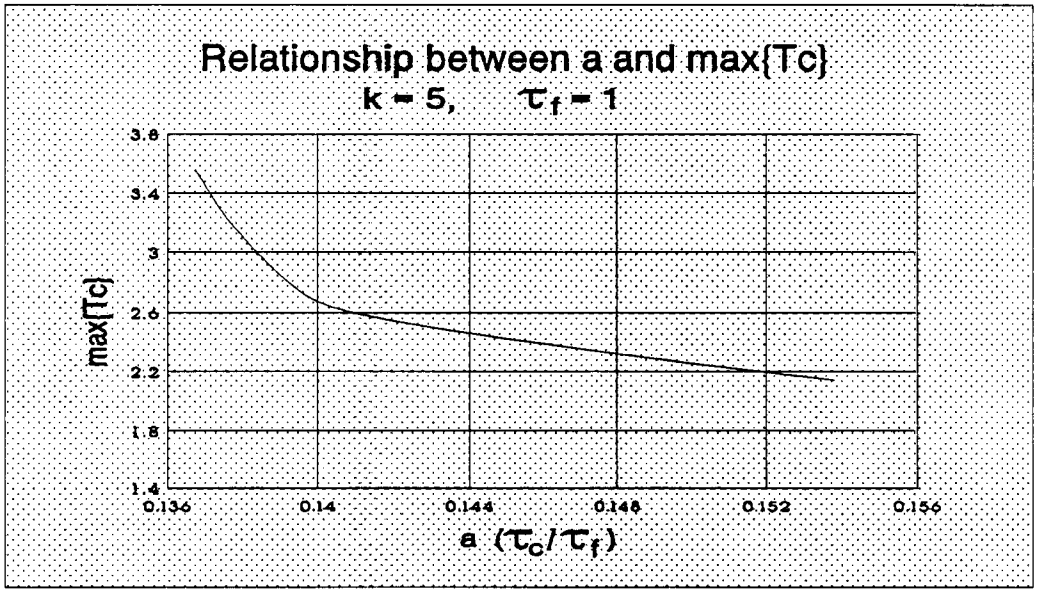


Figure 2.23 Relationship between a and max{Tc} (k=5)

and it's time constant is 1/k times that of the τ_f.

In the preceding theoretical analysis, it has been shown that the DCL has a dynamic response that is faster than the response of the ordinary temperature sensor. The response time can be reduced by selecting parameters k and the lag time constant L.

Comparing DCL and DCI, one can find that the DCL has no overshoot when $L \leq \tau_f/k$ while DCI cannot avoid the overshoot. In general, when L is set, it is hard to introduce overshoot to DCL because τ_f is hard to increase.

Another advantage of DCL is that DCL uses the response of only one TC while DCI needs the response of two TCs. A potential problem may be caused by using signals from two TCs if the response of both TC's have drifted. These signal errors could be compounded for the compensated signal at steady-state. So, DCL is more reliable than DCI.

For these reasons, only the DCTS with lagged signal method was developed.

CHAPTER III

EXPERIMENTAL ANALYSIS

3.1 Introduction

An important part of the development of a new temperature sensor is the testing to verify its theoretical basis and to incorporate it into real temperature measurements. Therefore, a plunge test and a random temperature fluctuation test were conducted for the new sensor: Dynamic Compensated Sensor with Lagged Signal (DCL). The following description of the experimental process and techniques includes the types of tests, the DCL construction, the testing facilities, and the conversion of voltage data to temperature data.

3.2 Types of Tests

Two test procedures were used for DCTS verification. The plunge test provides a step temperature change to the sensor and the random temperature fluctuation test simulates the real temperature measurement environment of the sensor.

A: Plunge Test

The standard plunge test is conducted by the rapid

movement of the sensor from an initial position in the air to a position in flowing water. There are other procedures to carry out a plunge test. But the common characteristic inherent in these testing procedures is that the sensor is exposed to a sudden (step) change in the ambient temperature. Then the sensor response during the transient is monitored, and the time constant (τ) is determined from the transient. In this experiment, the plunge test was conducted by placing the Dynamic Compensated Temperature Sensor in ice water and then moving it to boiling water rapidly.

B: Random Temperature Fluctuation Test

The random temperature fluctuation test is similar to the plunge test. The difference is that hot or cold water is gradually added to the container holding the sensor. By using this method, the temperature is changed randomly.

3.3 DCTS Sensor Construction

Figure 3.1 shows the construction of the DCTS with lagged signals. It has an ordinary thermocouple (fast sensor), a lag circuit, and a combining circuit. Figure 3.2 shows the lag and combining circuits.

As shown in Figure 3.2, the lag circuit is formed by two equal resistors, one capacitor, and one amplifier. The lag

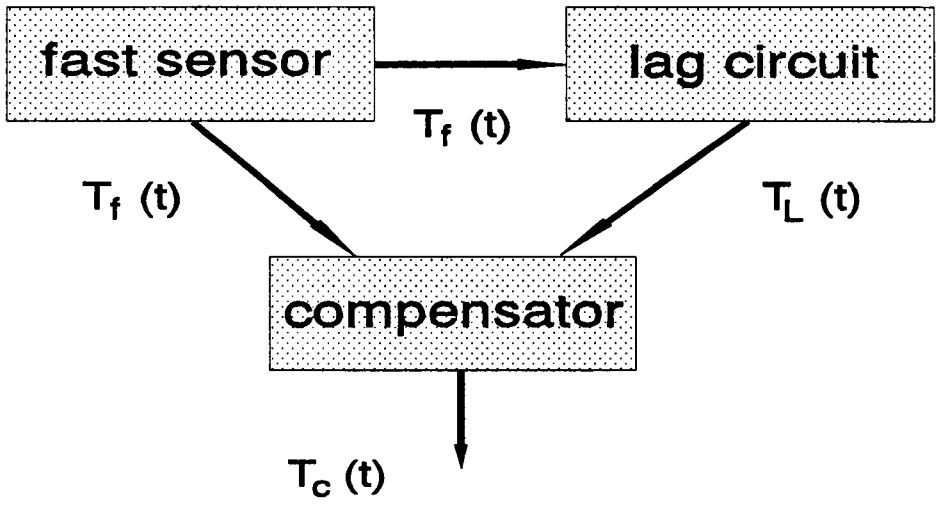


Figure 3.1 Construction of DCL

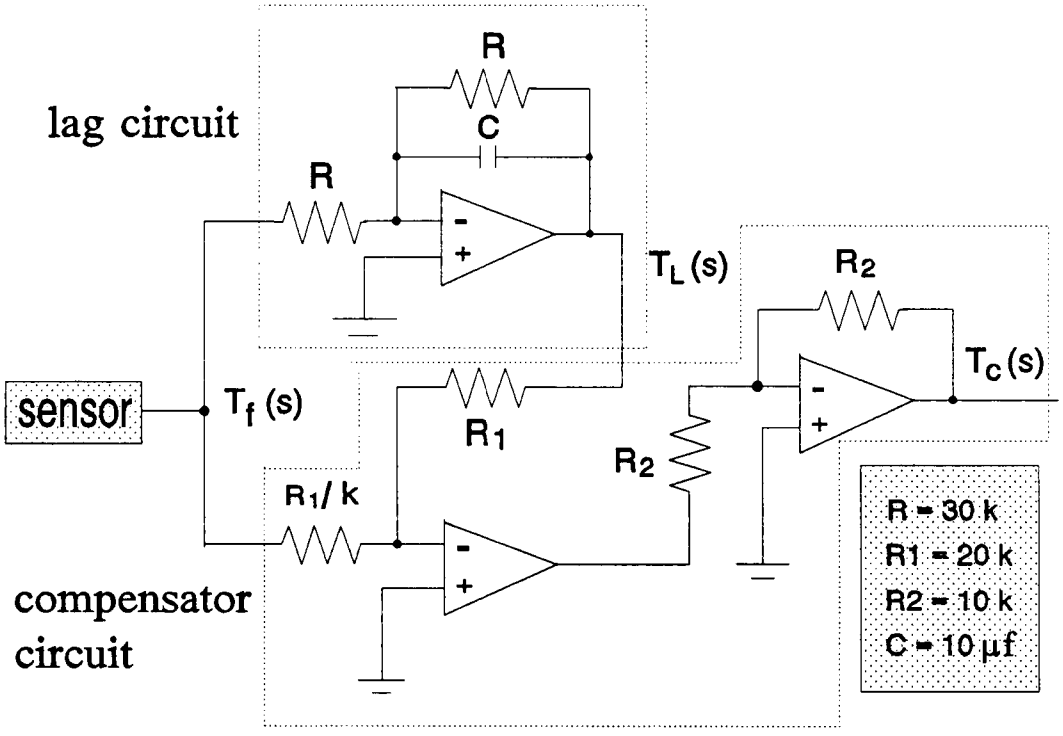


Figure 3.2 The DCL Circuit

time constant L is

$$L = RC \,. \tag{3.1}$$

The compensator circuit has one adder circuit and one converter. The transfer functions of $T_C(s)$ and $T_L(s)$ are

$$T_L(s) = -\frac{1}{RCs+1} T_f(s) \tag{3.2}$$

$$\begin{aligned} T_C(s) &= -R_1 \times [\frac{T_L(s)}{R_1} + \frac{T_f(s)}{R_1/k}] \times (-\frac{R_2}{R_2}) \\ &= k \times T_f(s) - \frac{k-1}{RCs+1} \times T_f(s) \end{aligned} \tag{3.3}$$

In the DCL tests, the parameter k was selected as 2, R_2 was set as 10 kΩ, and R_1 was 20 kΩ. Since in a nuclear power plant, a temperature sensor's time constant is typically about six seconds, the lag time constant L was set at approximately 3 seconds according to the theoretical analysis. Therefore, R was set as 30 kΩ, and C was 10 μf.

3.4 Testing Facilities

A: The Measurement System

The measurement system consists of the following components

1. The data acquisition and software system represents the intelligence center of the system. This system controls

the operation by which signals are acquired from the interface, performs all the computation and communication tasks, and analyzes the data.

2. An interface transmits the DCTS signals to the data acquisition system.

3. Signal conditioning makes the DCTS signals fit the requirements of the data acquisition system.

The whole system is shown schematically in Figure 3.3.

B: Data Acquisition System

In order to determine the time constant of the DCTS, a step change in the ambient temperature is needed. It can be produced by putting the sensor in ice water and then moving it to boiling water rapidly. With the temperature change, a voltage change is generated. The measurement signals were analog voltage signals. The data acquisition system converts the analog voltage signal to a digital signal, which can be analyzed by the computer.

Data acquisition was performed by the DT2801-A board and a PCLAB software package that were installed in a personal computer. The DC2801-A board is a high performance analog and digital input/output (I/O) board that can be programmed in BASIC to perform analog to digital (A/D) conversions, digital to analog (D/A) conversions, and digital input and output

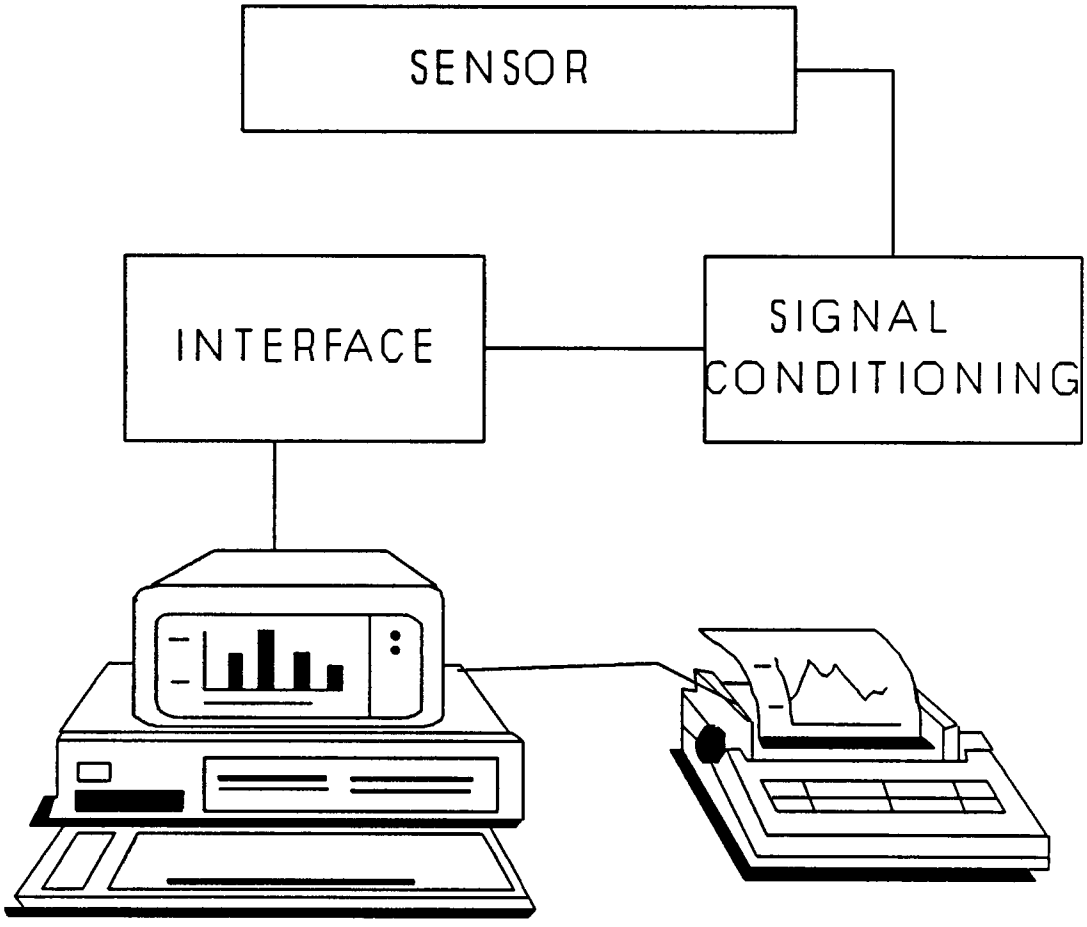


Figure 3.3 The Measurement System

transfers. Only A/D is used in this experiment.

PCLAB is a real-time software package designed for use with the DT2801 I/O boards. It consists of a BASIC "Save Module" that contains a number of machine language routines and a set of stand-alone data acquisition utilities.

Measurement of wide band process signals is performed with the program WDSAMPLE. It is a program using subroutines of the PCLAB library (PCFORLIB.LIB) to input different parameters to the DC2801-A board and to control the measurement process. Signals are connected to the board using a patch panel. User input to the program is as follows:

- the first and last channel to be measured (channel numbers of the A/D-board),
- the names (identification codes) and gains (isolation amplifiers, analog recorders, etc.) for the signals,
- a sampling interval,
- the total number of samples per channel,
- the gain of the A/D board (1,2,4 or 8), and,
- the name of the data file to be created.

Program MATCON is used to translate the binary data file produced by WDSAMPLE to a decimal data file.

C: Signal Conditioning

Signal conditioning is very important in transmitting the signals from the experiment to the measurement system. As

shown in Figure 3.3, the measurement system is made up of several components. It is common to partition the system at the transducer/signal conditioning interface. That is , the transducer is considered to be the signal source. Because signal conditioning affects the quality of the input signal, the ultimate performance of the system can be greatly influenced by the type of conditioning employed. The signal conditioning in this system now includes three channels of analog signal scaling, three channels of low-pass filtering, and an ice water bath.

(a). Analog Signal Scaling

A/D converters are designed to operate with "high-level" input signals. The DT2801-A A/D ranges include 0-10, +5 and +10 volts. When an input signal is below 1 volt, resolution and accuracy are degraded. Under these circumstances it is often appropriate to amplify the signal before the A/D converter. So, a two channel (TEC MODEL 901) amplifier was used. The amplifier's gain can be varied. When using the relationship between temperature and voltage, this gain will be accounted in the analysis program.

(b). Low-Pass Filtering

In order to eliminate the 60 Hz electrical noise caused by the electrical equipment and some other high frequency noise, a 40 Hz low-pass filter (TEC MODEL 901) is

used. Because the measurement signal frequency is far lower than 40 Hz, the filter will not influence the measurement signals.

D: Ice Water Bath

The purpose of the ice water bath is to create a 0°C reference junction for DCTS. The ice water bath consists of

A. A 13 inch high erlenmeyer flask glass barrel,

B. shaved ice made from distilled water,

C. 1/4 inch diameter and 12 inch long glass tubes,

D. mercury.

Figure 3.4 shows the structure of the ice water bath. The cone-shaped glass barrel is filled completely with the wetted ice. Mercury is poured into the glass tubes until it reaches a height of 1 to 2 inches. The mercury ensures temperature uniformity, electrical circuit continuity, and easy handling of wires. The glass tubes are inserted into multi-hole rubber stoppers for support. The tubes and the rubber stoppers are then submerged in the ice-water in the glass barrel.

E: Data Conversion

The experimental data resulted from voltage measurements from the A/D board. The voltage measurements were converted to temperature measurements. The following relationship between TC voltage and temperature was used. The conversion

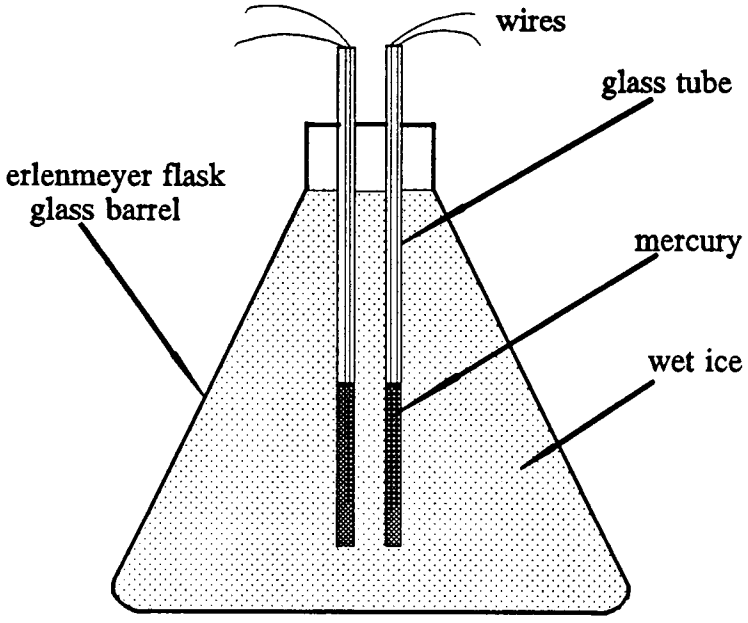


Figure 3.4 Ice Water Bath

was performed by computer program.

Temperature as a function of TC voltage T(V) is given by the following polynomial expression[2]:

$$T(^0c) = b_0+b_1V+b_2V^2+b_3V^3+b_4V^4+b_5V^5+b_6V^6+b_7V^7+b_8V^8 \qquad (3.4)$$

Equation (3.4) describes the temperature-voltage relationship for a type K thermocouple given by the ISA. It allows the conversion of measured voltages (in volts) to temperature (in ^{0}C) to an accuracy of +0.7 ^{0}C over the temperature range 0 to 1370 ^{0}C. Table 3.1 lists the values of the coefficients in Equation (3.4).

Table 3.1 Coefficients of Voltage Conversion to Temperature

NAME	COEFFICIENTS	TERM
b_0	2.26584602 $*10^{-1}$	V^0
b_1	2.415210900 $*10^{4}$	V
b_2	6.72334248 $*10^{4}$	V^2
b_3	2.210340682 $*10^{6}$	V^3
b_4	- 8.609639149 $*10^{8}$	V^4
b_5	4.83506 $*10^{10}$	V^5
b_6	- 1.18452 $*10^{12}$	V^6
b_7	1.38690 $*10^{13}$	V^7
b_8	- 6.33708 $*10^{13}$	V^8

CHAPTER IV

RESULTS

Two kinds of experiments were performed to demonstrate that the Dynamic Compensated Temperature Sensor with Lagged Signal can improve the ordinary temperature sensor's response time. The results are presented in two parts. In the first part, experimental results and theoretical simulation results of the plunge test are presented and compared. In the second part, experimental results of the random temperature fluctuation test are presented.

4.1 Plunge Test Results

In the set of three plunge tests, the DCLs with different lag time constants, but the same time constant of fast signals, were subjected to plunge temperature tests in order to measure their responses to a step temperature change.

The results of these experiments and the theoretical simulation results are given in Table 4.1 and Figures 4.1, 4.2, and 4.3. In these tests, the time constant τ of the fast sensor is 6.8 seconds, and the constant k is 2.

Table 4.1(a) and Figure 4.1 show the results when the lag time constant L is 3.4 seconds. The τ_C experimental result is

3.45 seconds, and the theoretical result is 3.4 seconds. From the results, it can be seen that a 50% improvement in response speed is achieved and that there is no overshoot.

When L is 2 seconds, the τ_C experimental result is 4.24 seconds, the theoretical result is 4.25 seconds. There is no overshoot in the $T_C(t)$ signal. This is shown in Table 4.1(b) and Figure 4.2.

When L is 6 seconds, the τ_C experimental result is 2.8 seconds, the theoretical result is 2.83 seconds. There is overshoot in the $T_C(t)$ signal. This is shown in Table 4.1(c) and Figure 4.3.

From the above results, it can be seen that the experimental results agreed closely with the theoretical simulation results. When $m(L/\tau)$ is 0.5, there is no overshoot and the improvement in τ is 50 percent. When m is smaller than 0.5, there is no overshoot. When m is greater than 0.5, there is an overshoot. For the same τ, τ_c increases with increasing L. These results agree with the theoretical analysis.

4.2 Random Temperature Fluctuation Test Results

The random temperature fluctuation test is important to determine the response of the DCL in real temperature measurement situations.

In nuclear power plants, the time constant of the

Table 4.1 DCL Plunge Test & Simulation Results

Table 4.1 (a)

	Theoretical Results	Experimental Results
max{Tc} (°C)	100.0	105.5
τ_c (sec.)	3.4	3.45
τ (sec.)	6.8	6.8
L (sec.)	3.4	3.4

Table 4.1 (b)

	Theoretical Results	Experimental Results
max{Tc} (°C)	100.0	103.5
τ_c (sec.)	4.24	4.25
τ (sec.)	6.8	6.8
L (sec.)	2.0	2.0

Table 4.1 (c)

	Theoretical Results	Experimental Results
max{Tc} (°C)	130.0	132.5
τ_c (sec.)	2.8	2.83
τ (sec.)	6.8	6.8
L (sec.)	6.0	6.0

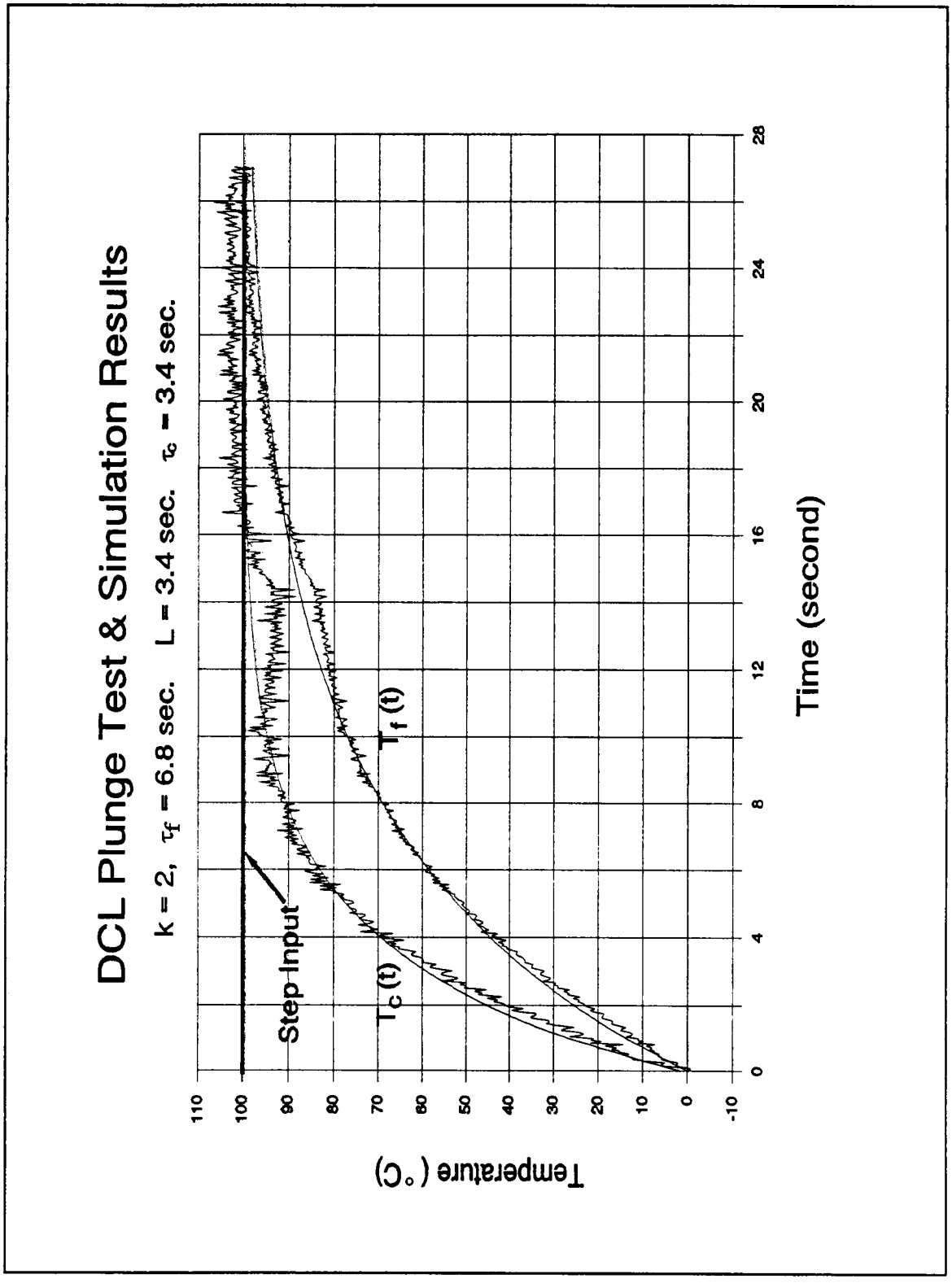


Figure 4.1 DCL (L=3.4 sec.) Response to a Step Temperature Change

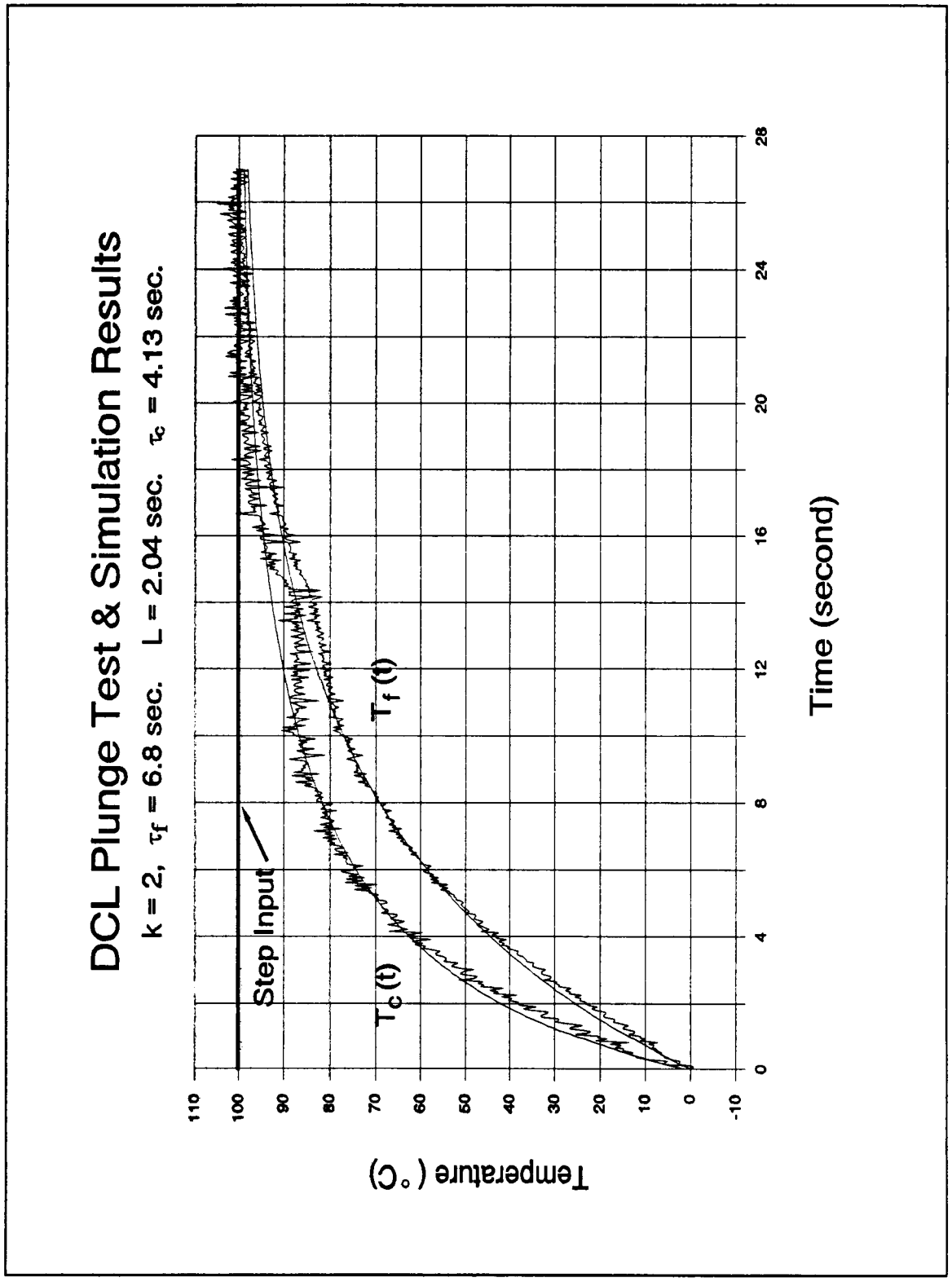


Figure 4.2 DCL (L=2 sec.) Response to a Step Temperature Change

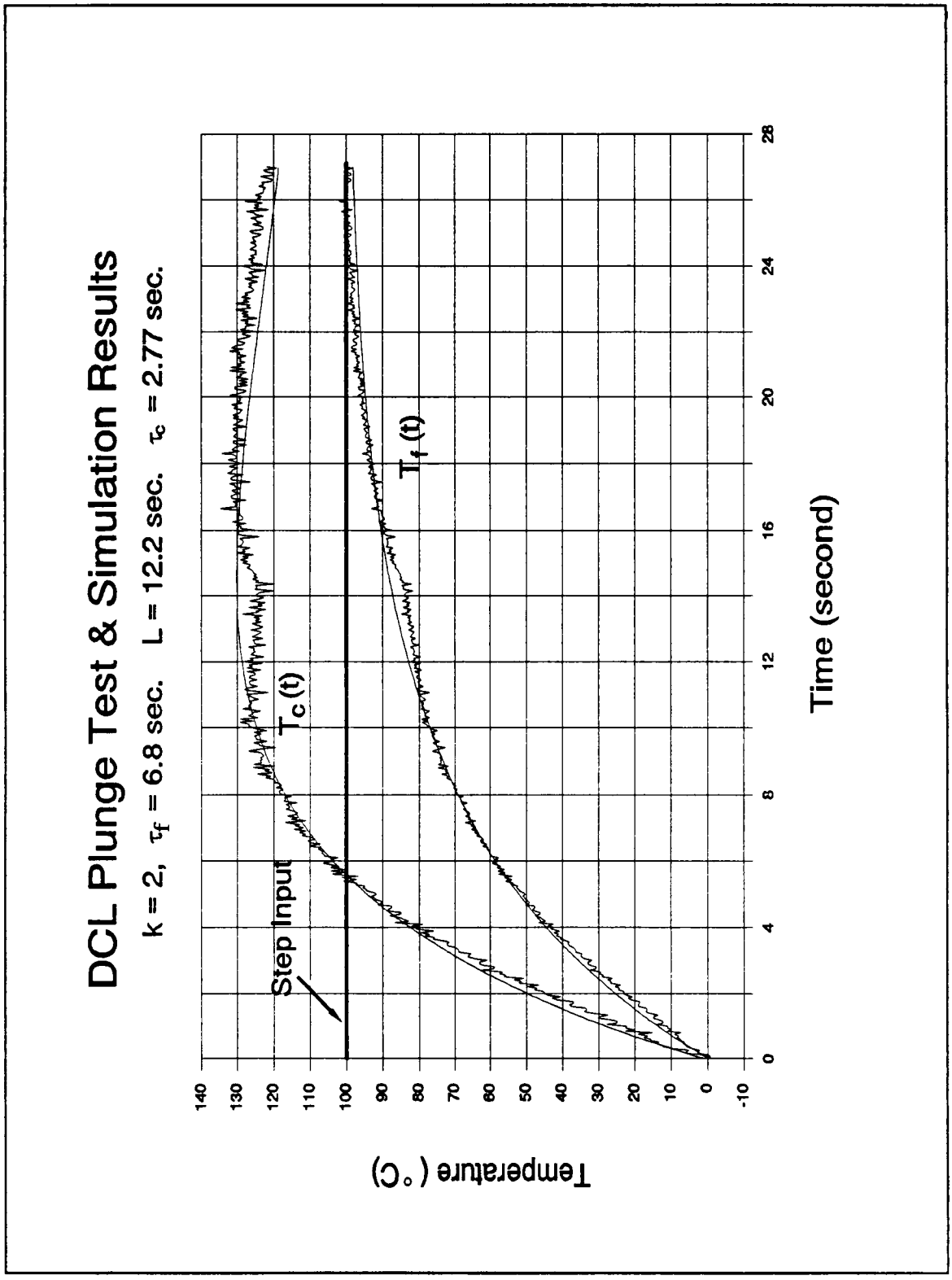


Figure 4.3 DCL (L=6 sec.) Response to a Step Temperature Change

ordinary temperature sensor is around 6 seconds. These time constants can be measured in-situ by using the loop current step response method (LCSR). But time constants change overtime and with changes in environmental conditions (such as temperature, pressure etc.). Therefore, we can not select the exact lag time constant of DCL when we apply it to in-situ temperature sensors. However, we can set a proper lag time constant which is appropriate for most sensors in a nuclear power plant. Based on the theoretical analysis, when k is 2 and the lag time constant L is near one half of the time constant τ of the ordinary sensor, we can get the compensated signal that has no overshoot and a 50 percent improvement in τ. In these experiments, L is set as 3.5 seconds. Two TCs with time constant τ as 9.2 sec and 9.6 sec are used to test the DCL.

Figure 4.4 shows the experimental results when τ is 7.4 seconds. Figure 4.5 gives the test results when τ is 9.2 seconds. In Figures 4.4 and 4.5, $T_R(t)$ indicates the true temperature. It is formed by using a vary fast responding thermocouple. $T_C(t)$ shows the compensated sensor's response to the input changing temperature signal. $T_f(t)$ shows the ordinary sensors response to the input signal.

It can be seen that the DCL can reduce the sensor's response time constant under the changing temperature conditions. L can influence the DCL as the theoretical analysis expected.

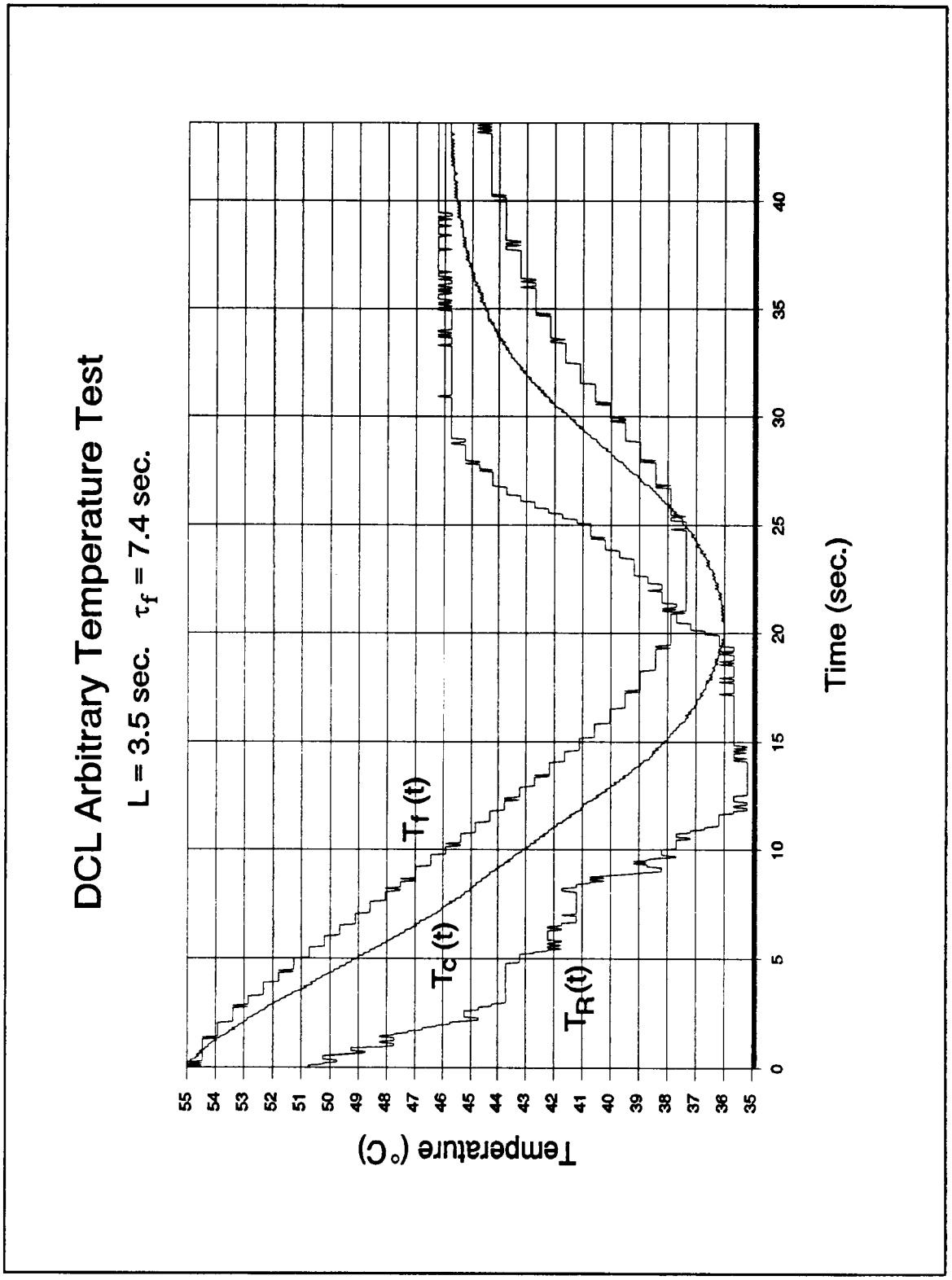


Figure 4.4 DCL (τ=7.4 sec.) Response to a Random Temperature Change

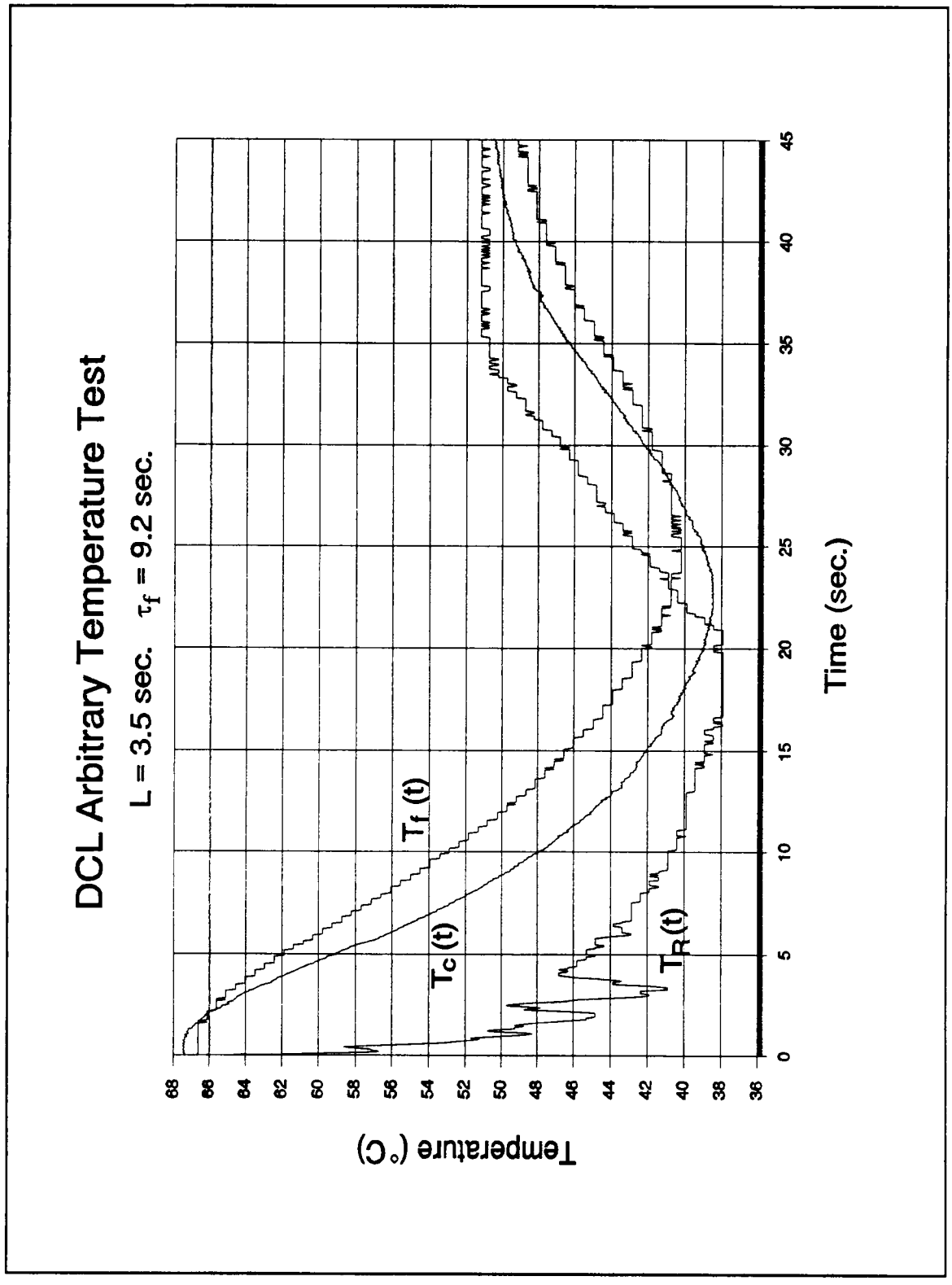


Figure 4.5 DCL (τ=9.2 sec.) Response to a Random Temperature Change

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This thesis has described the development of a new sensor, the Dynamic Compensated Temperature Sensor (DCTS), for improving the ordinary TCs or RTDs temperature sensors' response time. In this approach the signal compensated technique was used to create a compensated signal which has a shorter response time constant than that of an ordinary temperature sensor.

This thesis has developed the general theoretical analysis of the DCTS in the laplace domain and time domain. It also described the analysis, design, and construction of two types of compensated sensors: the Dynamic Compensated Sensor Using Independent Signals (DCI) and the Dynamic Compensated Sensor Using Lagged Signals (DCL). Through the discussion of these two kinds of new sensor, we find that the DCL has better behavior than that of the DCI.

Experiments were performed for the DCL and the results show that the DCL can achieve the design requirements.

An advantage of the Dynamic Compensated Temperature Sensor is that it can improve the temperature sensor's response time in an economical and easily performed way.

Therefore, it can provide a new technical method for nuclear power plant safety systems.

5.2 Recommendations for Future Work

Using DCL can improve a temperature sensor's response speed. However, when we want to avoid the over-prediction in the compensated signal, the amount of improvement in response time constant is limited. A potential method called the cascade lagged method might solve this problem.

The cascade lagged method is based on the Lagged method. In Lagged method, when k=2, $m(L/\tau_f)=1$, and the compensated signal (T_C) has no overshoot and its time constant is one half of the time constant of the original signal (T_f) which comes from the measurement. The formulas are

$$T_f = 1 - \exp(-t/\tau) \tag{5.1}$$

$$T_C = 1 - \exp(-2t/\tau) \ . \tag{5.2}$$

When taking the compensated signal as the original signal and going through the same process again, we get

$$T_f'(t) = 1 - \exp(-2t/\tau) \tag{5.3}$$

$$T_C'(t) = 1 - \exp(-4t/\tau) \tag{5.4}$$

which means the time constant of the second compensated signal

is 1/4 of the time constant of the original signal T_f.

What can be proved is that when this method is used n times, the nth compensated signal will be

$$T_C^n(t) = 1 - \exp(-2^n t/\tau) \qquad (5.5)$$

which means the τ_C is $1/2^n$ of the τ_f.

Figure 5.1 shows this as n=3. The time constant of the original signal τ_f is 6.0 sec., the time constant of the 3rd compensated signal is $\tau_f/8$ (0.75 sec.).

This method has been proved correct in theoretical analysis. However, further experimental work must be done to verify it.

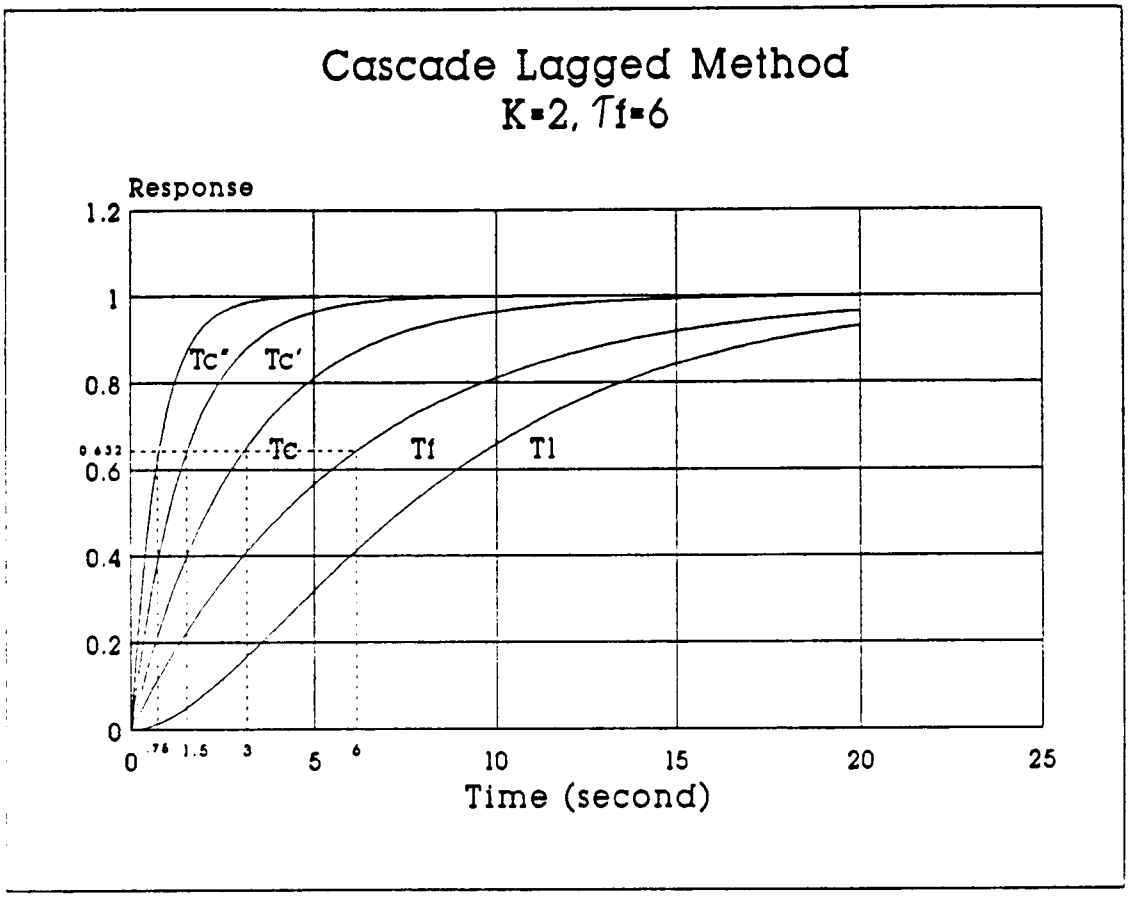


Figure 5.1 Cascade Lagged Method

REFERENCES

[1] Kerlin, T. W. et. al., Electric Power Research Institute, "Smart Temperature Sensor Research," Research Proposal, 1990.

[2] Kerlin, T. W., Shepard, R. L. Industrial Temperature Measurement. Instrument Society of America, Research Triangle Park, NC, 1982.

[3] Ogata, Katsukiko. Modern Control Engineering. Englewood Cliffs: Prentice-Hall, 1970.

[4] Gupta, S. C., Fundamentals of Automatic Control. John Wiley & Sons, Inc. 1970.

[5] Fich, Sylvan, Transient Analysis in Electrical Engineering. Prentice-Hall, Inc. Englewood Cliffs, N. J. 1951.

[6] Von Tersch, L. W. and Swago, A. W., Recurrent Electrical Transients. Prentice-Hall, Inc., NY. 1953.

[7] Robert N. Bateson, P. E., Introduction to Control System Technology. Merrill Publishing Company, A Bell & Howell Information Company, Ohio, 1989.

[8] Swago, A.W., and L.W. Von Tersch. Recurrent Electrical Transients. Prentice-Hall, New York, 1953.

[9] Upadhyaya, B.R.. An Introduction To Dynamics And Control. Knoxville: University of Tennessee, 1989.

[10] Natour, M. N., "Development of a Smart Temperature Measurement System Based on The Multi-Lead Thermocouple Concept," Dissertation, University of Tennessee, Knoxville, 1990.

[11] Natour, M. N., "Modelling and Testing of Industrial Thermometers," Thesis, University of Tennessee, Knoxville, 1986.

[12] "User Manual for DT2801 Series," Data Translation Inc., Massachusetts, 1984.

[13] "User Manual for PCLAB," Data translation Inc., Massachusetts, 1983.

[14] Distefance, III, J. J., Stubberud, A. R., and Williams, I. J., Feedback and Control Systems. Mcgraw-Hill Book

Company, New York, 1967.

[15] Hashemian, H. M., Kerlin, T. W., and Peterson, K. M., New Methods for Response Time Testing Industrial Temperature and Pressure Sensors. Pressure Temperature Measurements-FED-Vol.44/HTD-Vol. 58, The American Society of Mechanical Engineers, New York, 1986.

[16] Chohan, R. K., and Kerlin, T. W., Experimentation for The Dynamic Response of Industrial Temperature Sensors. Trans Inst MC Vol 8, No 2, April-June 1986.

[17] Kerlin, T. W., Shepard, R. L.. Hashemian, H. M., and Peterson, K. M., Response of Installed Temperature Sensors. Temperature, American Institute of Physics, 1982.

[18] Michalski, L., Eckersdorf, K., and Mcghee, J., Temperature Measurement. Jone Wiley & Sons Ltd. Baffins Lane, Chichester, West Sussex PO19 1UD, England, 1991.

[19] Taylor, H. R., and Navarro, H. A., Rapid Communication. J. Phys. E: Sci. Instrum., Vol. 16, 1983. Printed in Great Britain.

APPENDICES

APPENDIX A

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c=============================================================c
c                                                             c
c                      PROGRAM DCTS.FOR                       c
c                                                             c
c      This program is used to find the values of the         c
c     parameters in the analysis of Dynamic Compensated       c
c                  Temperature Sensor (DCTS)                  c
c                                                             c
c=============================================================c
c
       program DCTS.FOR
c
       integer k
       real maxTc, maxSc, mmaxSc, Tc, temp, m, Tf
c
c  open the output file
c
       open(unit=2, file='DCTS.dat', status='new')
c
c  calculate maxSc and Tc
c
       do 100 k=2, 10
          do 200 m=2.,30.,1.0
             temp = log( 1.0*(k-1)/(k*m) )
             maxSc = (k-1) * exp( temp/ (m-1) )
     &            - k * exp( m * temp / (m-1) ) + 1
             call ratios (k, m, tc, tf)
c
c  output the results to the output file
c
             write(2,*) k, m, maxSc, tc
200       continue
100    continue
c
       end

c-------------------------------------------------------------c
c                                                             c
c        This program is used to find the value of          c
c                          Tou-c                              c
c                                                             c
c-------------------------------------------------------------c
c
       subroutine ratios (k, m, tc, tf)
c
       integer k
       real tc, val, valprv, Sc, m, tf, Scpre
       logical  gotc
```

```
c
      gotc = .false.
      Scprv = 0.0
      valprv = 0.0
      val = 0.0
c
      do while (.true.)
         Sc = -exp(-val/(m*tf)+k*(exp(-val/(m*tf))
     &         - exp(-val/tf)) + 1
c
        if (Scprv.le.0.632.and.Sc.gt.0.632) then
          tc = (valprv+val)/2
          gotc = .true.
          print *, 'val=', val, tc, ye, k, m
          return
        endif
c
        Scprv = Sc
        valprv = val
        val = val +0.001
      enddo
c
      end
```

APPENDIX B

```
c=============================================================c
c                                                             c
c                        PROGRAM DCI.FOR                      c
c                                                             c
c   This program is used to find the proper parameters in     c
c    the design of Dynamic Compensated Temperature Sensor     c
c              Using Independent Signals (DCI)                c
c                                                             c
c=============================================================c
c
      program DCI.FOR
c
      integer k
      real maxTc, maxSc, maxTe, mmaxSc, Tc, Te, temp, m, Tf
c
c  Input the limits of max{Tou-c}, max{tou-e}, max{max{Tc}}
c  and Tf
c
      print *, 'Input: max{Tou-c} = '
      read *, maxTc
      print *, 'Input: max{Tou-e} = '
      read *, maxTe
      print *, 'Input: max{max{Tc}} = '
      read *, mmaxSc
      print *, 'Input: Tou-f = '
      read *, Tf
c
c  open the output file and output the limits
c
      open(unit=2, file='DCI.dat', status='new')
      write(2,*)  'max{Tou-c} = ', maxTc
      write(2,*)  'max{Tou-e} = ', maxTe
      write(2,*)  'max{max{Tc}} = ', mmaxSc
      write(2,*)  'k', 'm', 'max{Tc}', Tou-c', 'Tou-e'
      write(2,*)  ' '
c
c  calculate maxSc, Tc and Te
c
      do 100 k=2, 10
         do 200 m=2.,30.,1.0
            temp = log( 1.0*(k-1)/(k*m) )
            maxSc = (k-1) * exp( temp/ (m-1) )
     &              - k * exp( m * temp / (m-1) ) + 1
            call ratios (k, m, tc, te, tf)
c
c  output the results to the output file if qualified
c
          if(tc.le.maxTc.and.te.le.maxTe.and.maxSc.le.mmaxSc)
```

```
     &      then
              write(2,*) k, m, maxSc, tc, te
              end if
200        continue
100     continue
c
        end



c-------------------------------------------------------------c
c                                                             c
c         This program is used to find the value of           c
c                       Tou-c and Tou-e                       c
c                                                             c
c-------------------------------------------------------------c
        subroutine ratios (k, m, tc, te, tf)
c
        integer k
        real     tc, te, val, valprv, Sc, m, tf, Scpre
        logical  gotc, gote
c
        gotc = .false.
        gote = .false.
        Scprv = 0.0
        valprv = 0.0
        val = 0.0
c
        do while (.true.)
           Sc = -exp(-val/(m*tf)+k*(exp(-val/(m*tf))
    &           - exp(-val/tf)) + 1
c
           if (Scprv.le.0.632.and.Sc.gt.0.632) then
               tc = (valprv+val)/2
               gotc = .true.
           endif
c
           if (gotc.and.gote.) then
               print *, 'val=', val, tc, ye, k, m
               return
         endif
c
         Scprv = Sc
         valprv = val
         val = val +0.001
      enddo
c
      end
```

APPENDIX C

```
c=============================================================c
c                                                             c
c                      PROGRAM DCL.FOR                        c
c                                                             c
c      This program is used to find the values of the         c
c     parameters incthe analysis of Dynamic Compensated       c
c      Temperature Sensor Using Lagged Signals (DCL)          c
c                                                             c
c=============================================================c
c
       program DCL.FOR
c
        real k,m,a
        integer i,j
c
c  open the output file
c
        open (unit=2, file='DCL.dat',status='new')
c
c  calculate maxTc and Tou-c
c
        do 10 j=2,5
           do 5 i=1,50

           m = 0.1*i
           k = j

           call calc(k,m,a)

5          continue
10      continue

        stop
        end

c-------------------------------------------------------------c
c                                                             c
c        This program is used to find the value of            c
c                     Tou-c and maxTc                         c
c                                                             c
c-------------------------------------------------------------c
c
        subroutine calc(k,m,a)
c
        implicit none
        real k,m,a,x1,x2,x,y1,y2,y3,Tcmax

        x1=0
```

```
          x2=2.00

10        a=x1/2+x2/2
          if (m.eq.1) then
             x=0.368-exp(-a)+(k-1)*a*exp(-a)
          else
             x=0.368-(k*m-1)*exp(-a)/(m-1)
         &      +(k-1)*m*exp(-a/m)/(m-1)
          endif

          if (abs(x).le.0.0001) then
             goto 20
          else
             if (x.gt.0.0) then
                x2 = a
             else
                 x1=a
             endif
             goto 10
          endif

20        if (m.eq.1) then
             Tcmax=1+(k-1)*exp(-k/(k-1))
          else
             y1=1/(m-1)
             y2=m/(m-1)
             y3=k*m-1
             if (y3.le.0.0) then
                Tcmax = 1.
             else
                Tcmax=1+((k-1)**y2)/(y3**y1)
             endif
          endif
          write(2,30)k,m,a,Tcmax
          write(6,30)k,m,a,Tcmax
30        format(1x,4f10.5)

          end
```

APPENDIX D

DCL Plunge Test Results (L=3.4 sec.)

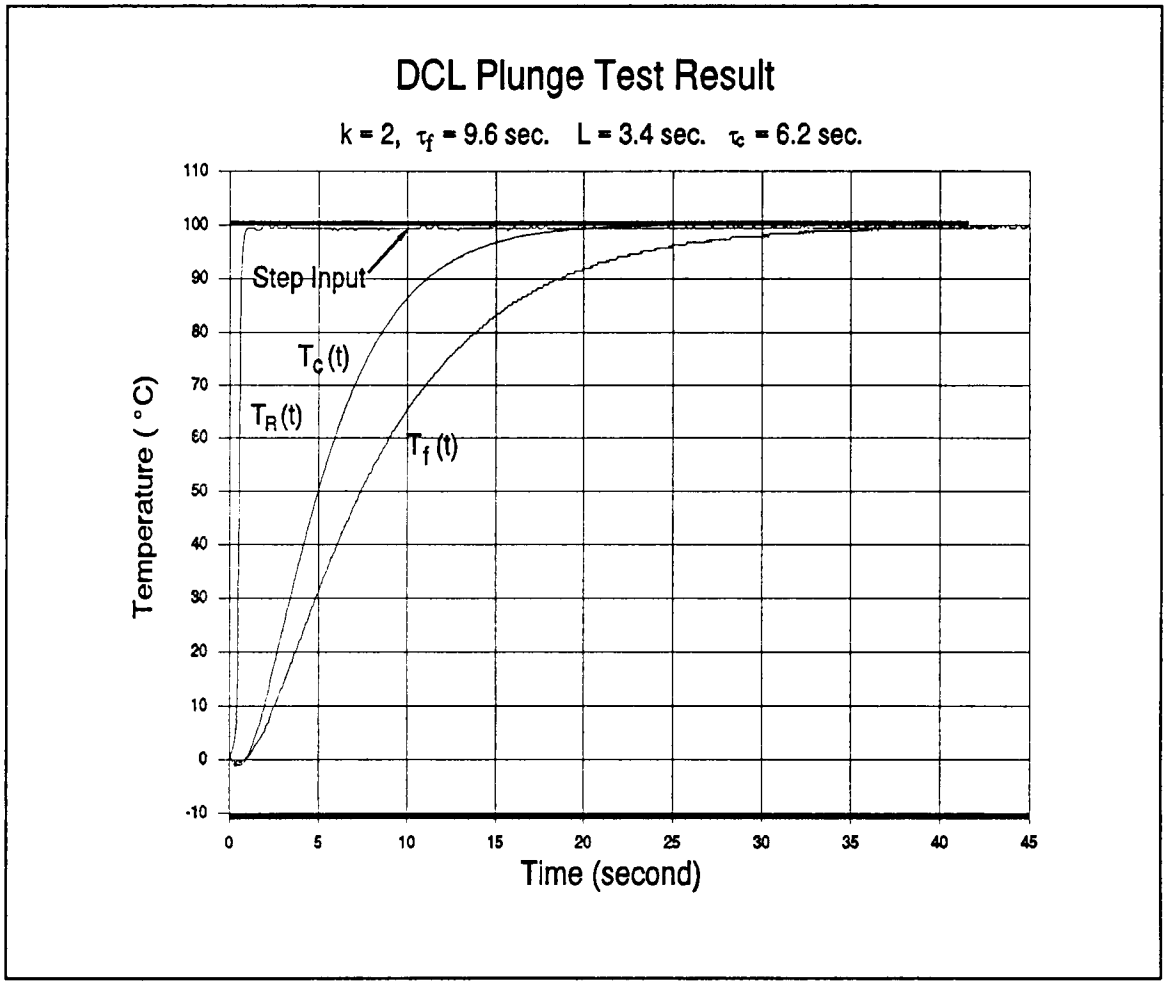


Figure D.1 DCL (τ_f=9.6 sec.) Response to a Step Temperature Change

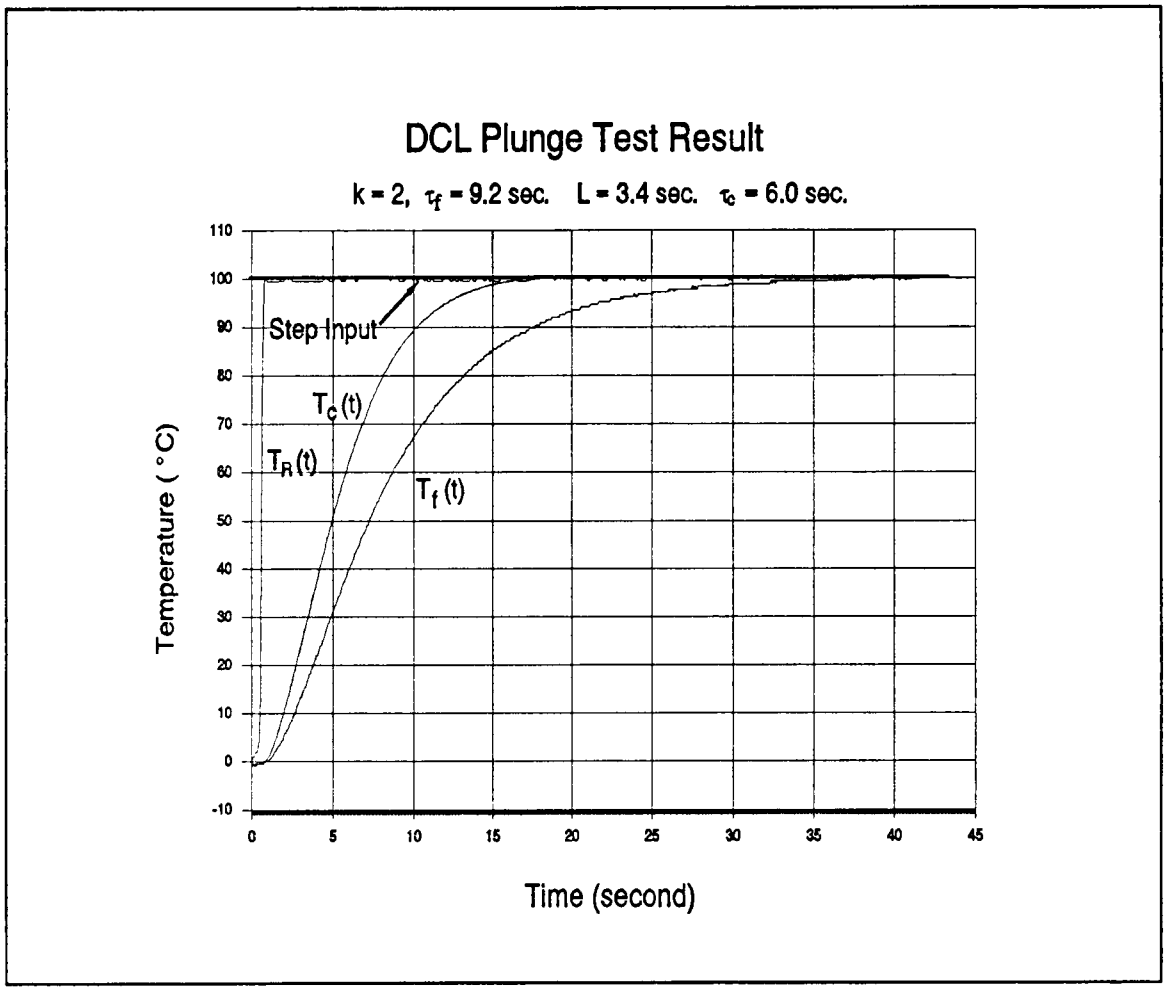


Figure D.2 DCL (τ_f=9.2 sec.) Response to a Step Temperature Change

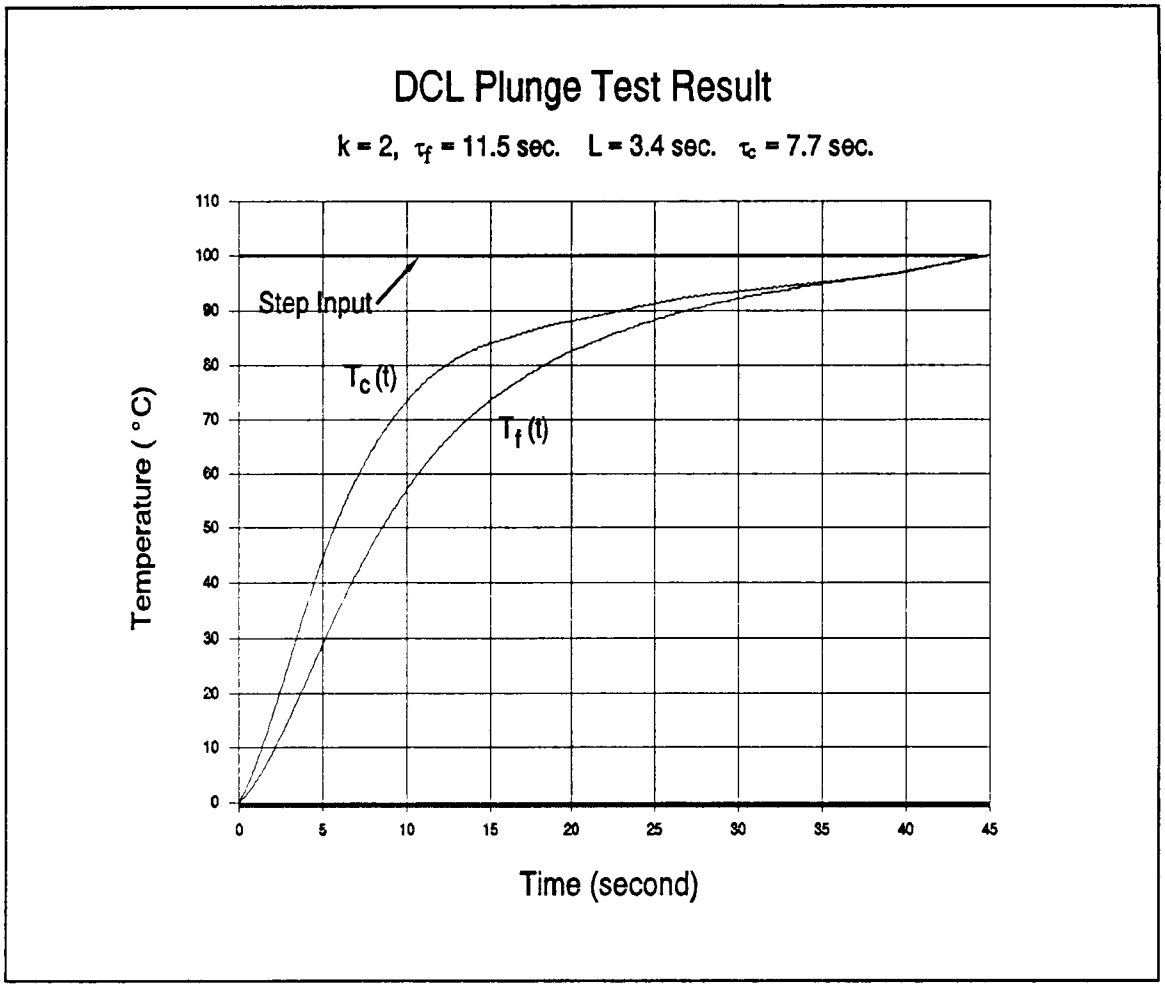


Figure D.3 DCL (τ_f=11.5 sec.) Response to a Step Temperature Change

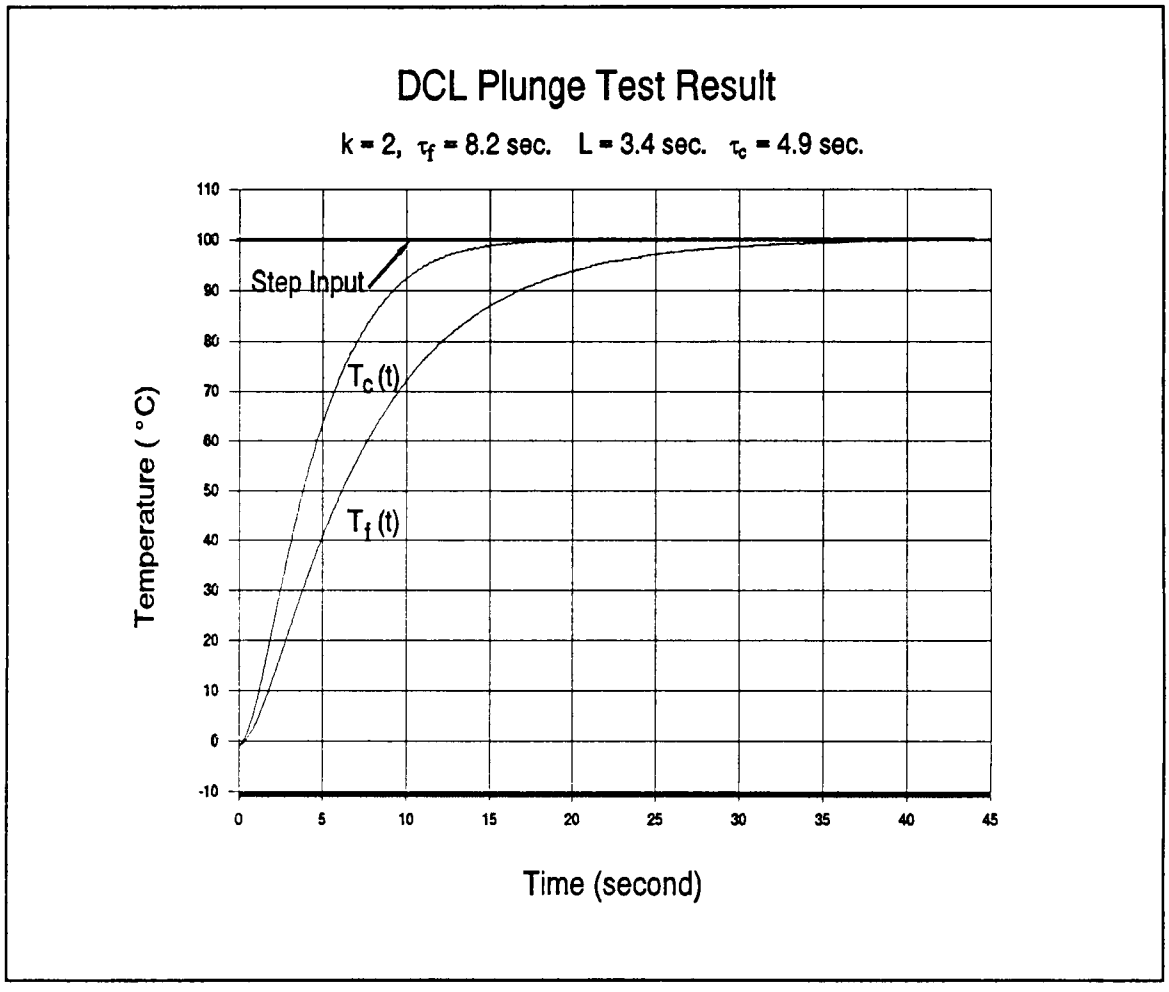


Figure D.4 DCL (τ_f=8.2 sec.) Response to a Step Temperature Change

VITA

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