A TELEMETRY CLIPPING CIRCUIT
AND HOLOGRAPHIC MODEL MATCHING

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by

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ABSTRACT

A TELEMETRY CLIPPING CIRCUIT
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This project report covers two independent tasks. The sections of the first part of the report deal with a dual range, double ended telemetry clipping circuit. They describe the requirements, design, computer analysis, breadboard testing, and performance evaluation of the device. A unique design configuration allows for rapid clipping range selection without component alterations.

In the second task, the concept of holography, or three-dimensional laser photography, is investigated and proposed as a method of determining the location of missiles in flight. The holographic image of a missile can be matched with a photograph of the missile in flight taken from a specified reference point. The feasibility of deriving accurate measurements from this approach is investigated in that part of the project report.
PART I

A TELEMETRY CLIPPING CIRCUIT
INTRODUCTION

The first part of this report discusses the design of a specialized dual range, double ended clipper. Equipment protection requirements are the subject of the first chapter, which establishes the need for a telemetry clipper. Through the observation of several different possible applications of the circuit a set of design specifications is established at the end of chapter 1.

Chapter 2 contains the basic circuit design information. The clipper is built up from a double ended zener diode circuit. A transistor model with a resistor divider network is substituted to allow for adjustment of the clipping thresholds. Addition of a buffer amplifier stage and constant current source reduce the clipping level fluctuations. Final modifications in chapter 3 minimize changes in circuit performance over the operating temperature range.

Computer analysis of the completed circuit design is presented in chapter 4. A specialized circuit simulation program is utilized to optimize component selection. In chapter 5 breadboard tests of the telemetry clipper are presented with an evaluation of performance under a wide range of environmental temperatures. A complete summary of the telemetry clipping circuit design and analysis is the topic of chapter 6.
CHAPTER 1

EQUIPMENT PROTECTION REQUIREMENTS

The transmission and reception of remotely monitored data involves sensitive electronic equipment and complex telemetry signals. Both the transmitting and receiving ends of a telemetry system, as well as the signal between them must be protected if the acquisition of telemetry data is to be accomplished effectively. The most critical requirement for signal protection is in the prevention of crosstalk between telemetry data channels in a multiplexed format. When large amounts of telemetry data are required, several separate channels are used and a multiplexed reducing scheme is provided for transmission. The block diagram of a typical telemetry transmitting system is shown in figure 1.1. Here several signal lines are time multiplexed down to three main trunks. These trunks then feed the input of three voltage controlled oscillators (VCOs). Their function is to convert the input amplitude information into variations in frequency over a relatively narrow bandwidth. The signals from the VCOs, each of which are in a different, but adjacent, bandwidth, are mixed together for common transmission.

The function of the clipper becomes clear if it is assumed that one of the telemetry lines is driven beyond
FIGURE 1.1. The Telemetry Transmitting System

its acceptable operating range limit. Following that
signal through the time multiplexer unit, a short burst
of overvoltage signal would, without the clipping circuit
for protection, appear on the input of a VCO. Since the
VCO is overdriven, its output would have frequencies out-
side the normal VCO operating bandwidth. This signal could
contain frequencies belonging to the bandwidth of one of
the other VCOs. The resulting crosstalk could interfere
with the information being transmitted. By inserting a
voltage limiter on the input line to each VCO, the cross-
talk arising from VCO saturation would be eliminated. The
clipping circuit would insure that, at worst, a VCO would
function at the extremes of its specified operating range,
but never beyond.
Another clipper is shown in figure 1.1 at the input to the transmitter. Its presence indicates a second important application of the device. Telemetry transmitters, like VCOs, are restricted to operate in a specific bandwidth. There are stringent government regulations covering telemetry standards which control such things as spurious emission, interference, and bandwidth\(^1\). These specifications could be violated if the transmitter input were driven beyond its designed capability. The telemetry clipper prevents that from happening.

The value of a telemetry clipper does not stop at the transmission phase either. There are useful applications for equipment protection at the receiving end. For permanent storage of telemetry information, either a multichannel tape or chart recorder is inserted to intercept the incoming signals. In the case of the tape recorder, overvoltages can cause tape saturation and adjacent channel crosstalk. For the chart recorder, serious pen damage can result from detection and tracking of voltages of very large amplitude. Inserting a telemetry clipper on the input lines to these devices would reduce the likelihood of such damage occurring.

Although low, the probability of a signal voltage appearing outside its normal operating limits is significant enough to require some degree of protection. Dangerously high or low signals can arise from a variety of different sources. On a missile system in an operational
mode, the dramatic changes in environmental conditions, such as temperature, humidity, shock, or altitude, may spur premature device failures. These failures could easily propagate unrealistic signals throughout the telemetry transmitting system. A head-on encounter with a strong infra-red radiation source by an IR detector or intense radar reflections presented to a radar guided missile directly on target could saturate the sensitive receiving equipment, producing exaggerated signals. On the receiving end, improper shielding, intermittent ground connections, or simply careless equipment handling could generate spurious responses of damaging magnitude. An unexpected, sudden increase in signal reception could catch the automatic gain control (AGC) circuitry at a most sensitive setting. With insufficient time to recover, the data received and passed through the circuitry could overdrive the recording equipment. Each of these situations could occur in the course of a telemetry study. A set of telemetry clippers strategically placed throughout the communications system would alleviate many of the potential complications attributable to out of range voltage signals.

Several applications of a telemetry clipping circuit have been identified. It will now be shown how these applications determine the selection of appropriate design criteria. The voltages in question, for telemetry systems, are divided into two specific ranges. These are 0.0 to +5.0 volts and ±2.5 volts. It is common practice to find
both ranges in use under normal conditions, and therefore it would be advantageous to design a clipper capable of handling both of these ranges in the same circuit. Furthermore, any signal falling within the range of voltage limits should be passed through the clipper unaltered. A clipping cushion of $\frac{1}{2}$ volt should be allowed on both the lower and upper limits, in order to maintain the linearity of the response within the range limits. These input-output response characteristics are shown in figure 1.2.

![Graphs showing input-output voltage characteristics](image)

**FIGURE 1.2.** Input-Output Voltage Characteristics

The circuit must be designed to operate on power supplies which produce either 10 volts or 15 volts, both positive and negative in polarity. The voltage clipper, to be a general purpose device, should be insensitive to supply voltage fluctuations. In other words, small drifts in supply voltage should not significantly affect the established clipping levels. The clipper will be expected to demonstrate clipping level stability efficiently over the environmental temperature range of $-55^\circ C$ to $+125^\circ C$. 
Again, for general applications, a ceiling of one percent change in voltage for each threshold should be allowed. That means each threshold could drift by no more than 0.05 volts for a 5 volt telemetry system over the entire temperature range.

The frequency response of the circuit is dependent on the particular application in question. For VCO overdrive protection, the bandwidths established for FM subcarrier channels in the Inter-Range Instrumentation Group telemetry standards\(^3\) determine the appropriate ceiling frequency. The highest nominal frequency response encountered is specified as 4950 Hz. The telemetry clipper should transfer normal signals linearly through this frequency. Now, the frequency of the signal entering the transmitter is the same as the highest VCO output passing through a mixing stage (see figure 1.1). Therefore, for transmitter voltage protection the clipper should pass signals through the highest possible VCO output frequency. Again referring to the telemetry standards\(^4\), this frequency is 189,750 Hz. 200 KHz is, therefore, a reasonable upper frequency limit for the telemetry clipper. This limit is realistic since the recording equipment on the receiving end will not be required to copy signals higher in frequency than those encoded for transmission. Although the response of telemetry tape recorders is much higher at fast tape speeds\(^5\), this anticipated limit will not be exceeded for most general applications.
Chart recorders present a different problem. Their frequency response is limited by the inertia of the pen assembly to a few hundred hertz. These devices, therefore, do not impose any further requirements on the upper frequency limit of a telemetry clipper. Since the sensitive pens can be damaged from even a DC overvoltage applied to the pen control circuitry, the clipper must be able to monitor constant voltage levels and limit them when necessary. Thus, a lower frequency limit of straight DC must be included as an additional constraint.

The telemetry clipper design specifications are summarized in table 1.1. Other parameters, such as input-output impedance and total power consumption, were left open to provide a degree of flexibility in the design phase. A consistent effort to minimize power, maximize input impedance and minimize output impedance was observed throughout the design.
TABLE 1.1.
Specified Design Criteria

Clipping Ranges
Range I: 0.0 to +5.0 volts
Range II: -2.5 to +2.5 volts

Absolute Clipping Limit
Range I: -0.5 to +5.5 volts
Range II: -3.0 to +3.0 volts

Stability
±0.05 volts for each threshold, both ranges

Frequency Response
DC to 200 KHz

Operating Temperature
-55°C to +125°C

Power Supply Requirements
±10.0 volts or ±15.0 volts
A voltage clipper is a special circuit which limits the voltage between a signal line and ground, or between two signal lines, from exceeding a specified value. A very simple ideal clipper is shown in figure 1.3a. The diode D1 is normally reverse biased by the voltage \( V_B \), and the input voltage appears unaltered on the output terminals. When the input voltage exceeds \( V_B \), then D1 conducts, and the output is strictly limited to the \( V_B \) voltage. The characteristic response of this circuit is shown in figure 1.3b.

![Diagram of a basic voltage clipper](image)

**FIGURE 1.3. A Basic, Ideal Clipper**
Unfortunately, this design requires a highly accurate voltage source, $V_B$ in conjunction with D1, to establish the clipping threshold. Such a source will not be available in the operational environment which the telemetry clipper is likely to encounter. An improved design may be achieved by substituting a zener diode for the ideal diode in figure 1.3a and eliminating the voltage source $V_B$. Furthermore, inserting a second zener diode in series with the first one, but opposite in polarity, will insure that excessive voltages are clipped in the negative as well as the positive direction. This double ended action is a necessary requirement in the final telemetry circuit design.

Figure 1.4a depicts a simple double ended zener circuit with its associated characteristic curve shown in

![Double Ended Zener Clipper](image)

**FIGURE 1.4.** Double Ended Zener Clipper
figure 1.4b. As the input voltage is increased in a positive direction, D1 becomes reverse biased providing a high impedance bridge across the output. Further increases in input voltage appear at the output terminals until the reverse breakdown of D1 is reached. At that point the zener conducts; and, because of the forward biasing of D2, the output voltage is maintained at the breakdown voltage of D1. The same situation exists when $V_{in}$ is increased from zero in a negative direction. This time D2 is reverse biased and it conducts only when its reverse breakdown voltage is reached. Similar analysis shows that this voltage will be clipped at the output in the negative direction.

If the zeners in figure 1.4a are matched, then the characteristic curve of figure 1.4b will be realized. If they are not matched, the clipping will not be symmetric. This circuit does not provide a means of switching between two separate clipping ranges. This requirement of the telemetry clipper can be met, however, if the two zener diodes are replaced by the two transistors as shown in the configuration of figure 1.5.

The PNP transistor Q1 and the NPN transistor Q2 of figure 1.5a function in a similar capacity as the zener diodes of figure 1.4a thus producing a double clipping effect on the input voltages. However, the actual clipping thresholds of figure 1.5b are now established by the voltages on the bases of the transistors. These base
FIGURE 1.5. Double Ended Transistor Clipper

voltages are determined by the resistor dividers R1, R2 and R3, R4.

Normally, with the input voltage set to zero, or a very low level, both transistors are off. Analysis of the circuit proceeds as follows: Starting with Q1, the collector is connected directly to the negative supply. The base is maintained at some positive potential. With low level input signals, the emitter of Q1 is likewise low, and the base-emitter junction of this PNP transistor is reverse biased. The Q1 transistor remains turned off until the input voltage is raised to the base potential plus Q1's V_{BE}. At that point, the transistor turns on and the output voltage is clipped at the upper threshold level. The lower half of the circuit in figure 1.5a, namely Q2, R3, and R4, is a mirror image of the upper half and as such
functions identically, clipping the output to the lower threshold.

This circuit shows high promise in meeting the design requirements of the telemetry clipper. It has the capability of shifting the clipping threshold levels by simply changing the ratios of the resistors in the divider networks. Furthermore, several channels of clipping could be implemented by replicating a series of Q1, Q2 transistor pairs. This would be accomplished by hooking all the Q1 bases together, all the Q1 collectors to \( V_- \), all the Q2 bases together, all the Q2 collectors to \( V_+ \), and the emitters of each Q1, Q2 pair to the input and output of a separate information channel. There is one drawback in doing this, however. If one channel is driven into the clipping mode, then the base current of the clipping transistor changes. Since its bias current is derived from the resistor divider network, the node voltage (and, hence, the threshold voltage) of all the other common transistor bases would change. Clipping would then occur at a different point for all remaining channels when one channel engages in active limiting. To avoid this, a simple buffer amplifier stage can be added to the circuit as shown in figure 1.6. Transistors Q1, Q2 and Q3, Q4 form the active clipping transistor pairs for channels 1 and 2. The buffer amplifier consists of Q5 and Q6 configured as emitter followers. With high resistances for R7 and R8, these transistors simulate a voltage source whose potential is
FIGURE 1.6. Addition of Buffer Amplifier Stage

that of the respective base voltage plus the transistor's $V_{BE}$. The clipping transistors, being connected to the emitter of the buffer transistors, function as described before, but without loading down the resistor divider networks. Thus, even when one of the channels is driven into clipping, the threshold levels for the other channels remain unaltered.

Clipping threshold stability has now been established for several channels simultaneously, but there are still requirements for the clipping levels to be independent of changes in the supply voltage and temperature. The circuit, as shown in figure 1.6, will not provide this. On close examination it can be seen that the voltage on the base of transistor $Q_5$ is determined by the current flowing through resistor $R_2$ to ground. Likewise, $Q_6$'s
base voltage is found from the current through $R_3$. If these currents were constant irregardless of the supply voltage levels, then the objective of supply voltage independence would be met.

A stable current can be achieved by replacing the resistors $R_1$ and $R_4$ in figure 1.6 with two constant current sources. There are many such possible current sources to choose from. The one selected for this application has been used for similar objectives in other circuits and will satisfy the requirement over the range of supply voltages. When the positive supply voltage in figure 1.7 is connected to the circuit, transistor $Q_1$ turns on raising the potential at point "A". At the same time, $Q_2$ turns on raising

![FIGURE 1.7. A Constant Current Source](image)
the potential at point "B". Transistor Q3 is properly biased and turns on, raising the voltage at point "C". As soon as the voltage at point "C" is greater than the one at point "D" by Q4's $V_{BE}$, Q4 turns on and lowers the potential at point "A". Q3 and Q4 then regulate the voltage at point "D" by controlling the current flow, $I_C$, through R2. That current flow is derived from R1 and Q4's $V_{BE}$ junction voltage by a direct application of ohm's law. For matched transistors, equation (1) indicates the relationship.

$$I_C = i_1 + i_2 = 2i_1 = 2 * \frac{V_{BE}}{R_1}. \quad (1)$$

If two of these constant current sources are inserted in the original circuit of figure 1.6 to replace R1 and R4, as is shown in figure 1.8, then the clipping thresholds will be independent of supply voltage fluctuations. The telemetry clipper, even with these added current sources, is still limited to only one clipping range. The design specifications require a second range of $-0.5$ volts to $+5.5$ volts. When these limits are compared with the symmetric range of $-3.0$ volts to $+3.0$ volts, one range can be derived from the other by a simple 2.5 volt offset in both thresholds. Therefore, the same circuit design can be used if a 2.5 volt offset voltage is introduced when the alternate range is selected.

Since there are already two constant current sources built into the design, a constant offset voltage can be constructed by inserting a resistor in series with one of
FIGURE 1.8. Addition of Constant Current Sources and Range Selection Resistor
the current sources. The offset is positive, therefore the
offset resistor has been placed between R4 of figure 1.8
and the lower current source. This pushes up the voltage
at nodes "C" and "D" by the required amount when G1 is
grounded. The complete initial telemetry clipping circuit
shown in figure 1.8 was utilized for both computer analysis
and breadboard tests as will be explained in subsequent
chapters.

The determination of the value of $R_{off}$ in figure 1.8
depends on the values of other circuit parameters. If the
now optional ground terminal is selected as node G1, then
the voltage developed across $R_{off}$ from equation (1) is:

$$V_{R_{off}} = \frac{2V_{BE}}{R1} \times R_{off}$$  \hspace{1cm} (2)

Solving, then, for $R_{off}$,

$$R_{off} = \frac{(-3.0 + 2V_{BE} + 2.5) R1}{2V_{BE}} = R1 - \frac{R1}{4V_{BE}}$$  \hspace{1cm} (3)

The voltage at nodes "C" and "D" are both determined
from the current of the upper current source. Employing
equation (1) once again,

$$V_C = \frac{2V_{BE} (R2 + R4 + R_{off})}{R1}$$  \hspace{1cm} (4)

$$V_D = \frac{2V_{BE}}{R1} \times R_{off}$$  \hspace{1cm} (5)

Calculating the clipping threshold equations,
\[ V_{T+} = V_A + V_{BE} = V_C + 2V_{BE} \]

\[ V_{T+} = \frac{2V_{BE} (R2 + R4 + R_{off})}{R1} + 2V_{BE} \]  \hspace{1cm} (6)

and

\[ V_{T-} = V_B - V_{BE} = V_D - 2V_{BE} \]

\[ V_{T-} = \frac{2V_{BE} \cdot R_{off}}{R1} - 2V_{BE} \]  \hspace{1cm} (7)

When the ground connection is moved from node G1 to node G2, these equations become:

\[ V_{T+} = V_A + V_{BE} = V_C + 2V_{BE} \]

\[ V_{T+} = \frac{2V_{BE} \cdot R2}{R1} + 2V_{BE} \]  \hspace{1cm} (8)

and

\[ V_{T-} = V_B - V_{BE} = V_D - 2V_{BE} \]

\[ V_{T-} = -\frac{2V_{BE} \cdot R4}{R3} - 2V_{BE} \]  \hspace{1cm} (9)
CHAPTER 3

ADVANCED CIRCUIT DESIGN

Reviewing the specified design criteria of table 1.1, the final telemetry clipping circuit must not only accommodate the two clipping ranges, but must exhibit stability with temperature changes. There are two types of devices used in the circuit of figure 1.8, namely resistors and transistors. The temperature stability of the resistors may be controlled to within ±25 ppm/°C if care is exercised in resistor type selection. This is not the case for transistors, however. At the junction of N and P type material in a semiconductor device, the voltage across the junction as developed by Shockley is given by:

\[
V_j = \frac{kT}{q} \ln\left(1 + \frac{I_F}{I_R}\right)
\]

Relating this to the transistor model, the two NP junctions between the base and emitter and the base and collector generate the following equations:

\[
V_{BE} = \frac{kT}{q} \ln\left(1 + \frac{I_{EF}}{I_R}\right)
\]

\[
V_{CB} = \frac{kT}{q} \ln\left(1 + \frac{I_{CF}}{I_R}\right)
\]

Typically for forward currents of one milliamp and reverse leakage on the order of 10^{-15} amp, the temperature
sensitivity of the base-emitter voltage can be calculated from:

$$\frac{\Delta V_{BE}}{\Delta T} = \frac{k}{q} \ln(1 + \frac{I_{BE}}{I_R})$$  \hspace{1cm} (13)$$

as:

$$\frac{\Delta V_{BE}}{\Delta T} = \frac{8.616 \times 10^{-5}}{1} * \ln(1.0 * 10^{12})$$

which reduces to:

$$\frac{\Delta V_{BE}}{\Delta T} = -2.38 \text{ mV/°C}$$  \hspace{1cm} (14)$$

Therefore, everywhere a $V_{BE}$ term appears in a voltage equation, the sensitivity of that voltage to temperature will be governed by equation (13) with the numerical approximation given in equation (14).

The design criteria outlined in table 1.1 specifies a clipping drift of no more than ±0.05 volts over the entire temperature range of -55°C to +125°C. Numerically, this establishes the sensitivity level given in equation (15).

$$\frac{\Delta V_T}{\Delta T} = \frac{\pm 0.05}{125 - (-55)} = \pm \frac{0.05}{180} = \pm 0.28 \text{ mV/°C}$$  \hspace{1cm} (15)$$

The required circuit temperature sensitivity is an order of magnitude smaller than the sensitivity of an individual transistor junction. Therefore, transistor balancing must be integrated into the design to compensate for temperature effects.
Examining figure 1.8 closely, it can be seen that the voltages across the resistors \( R_2, R_4, \) and \( R_{off} \) are determined by the two constant current sources. The actual current is dependent on the thermal sensitivity of these sources. The first step in stabilizing the clipping thresholds is to eliminate the dependence of the circuit on the thermal changes in the current sources. They should only provide supply voltage independence.

One effective way of making a voltage divider accurate with temperature variations is to insure that a constant voltage is applied across the resistor string. A zener diode will offer such a constant voltage\(^{11}\). The approach chosen in the redesign of the telemetry clipping circuit of figure 1.8 was to insert a transistor zener diode equivalent circuit between nodes "C" and "D", shown as Q9 in figure 1.9. Then, by selecting either node G1 or G2 as ground, the absolute clipping thresholds could be shifted together, while the voltage difference between the upper and lower levels remained the same. A modified constant current source was used to replace the two current sources of figure 1.8. This will insure that the same current flows through the collectors of both Q2 and Q4 in the new circuit.

Several other components have been added to the telemetry clipping circuit of figure 1.9 that were not in figure 1.8. These are designed to offset the temperature effects of the buffer amplifier and clipping transistors.
FIGURE 1.9. Revised Design for Temperature Stability
Q14, Q15, Q16, and Q17. Transistor Q10 has been included to isolate the right hand half of the circuit from the zener equivalent circuit, the constant current source, and the R1, R2, R3 resistance network. The section consisting of R5 and R6 is designed to provide a resistor divider for setting the upper clipping level. Components R7, R8, and Q11 are included to compensate for temperature effects on the upper clipping threshold. The remaining section of R9, Q12, and Q13 allows two semiconductor junctions for offset of temperature effects and a resistor to provide bias current to the base of Q15 (node "B", figure 1.9).

A quick analysis for temperature dependence of the clipping levels indicates that the diodes Q12 and Q13, if properly biased, do in fact cancel the effects of temperature on Q15 and Q17 for the lower threshold level on both clipping ranges. The change in the output, therefore, tracks any change in the potential of node "D" in figure 1.9.

The upper clipping threshold voltage sensitivity is a bit more complex to explain. The thermal effects on the base-emitter junction of transistors Q14 and Q16 add together at node "A". To stabilize the output, therefore, the circuitry to the left of node "A" must provide a voltage drift with temperature equal to the contribution from Q14 and Q16, but opposite in direction. Since the potential of node "A" is set by a voltage divider consisting of R5 and R6, two equations must be written to
describe the voltage sensitivity limits on either side of the resistors. Assuming first that \( R_5 \) is much larger than \( R_6 \) so that \( R_6 \) can be neglected, equation (16) applies.

\[
V_{T+} = V_D + 2V_{BE}
\]  

(16)

Again, the voltages are specified in terms of the potential at node "D", \( V_D \), since the lower thresholds have already been shown to be stable with this voltage. The sensitivity of \( V_{T+} \) to temperature can be found from the derivative of equation (16).

\[
\frac{\partial V_{T+}}{\partial T} = 2 * \frac{\partial V_{BE}}{\partial T}
\]  

(17)

In the other situation where \( R_6 \) is much larger than \( R_5 \), the output voltage is a function of the zener equivalent circuit, Q9. That is,

\[
V_{T+} = V_D + V_Z - V_{BE} - \frac{R_7}{R_7 + R_8} * V_{BE} + 2V_{BE}
\]  

(18)

The resulting sensitivity is:

\[
\frac{\partial V_{T+}}{\partial T} = \frac{\partial V_Z}{\partial T} + (1 - \frac{R_7}{R_7 + R_8}) * \frac{\partial V_{BE}}{\partial T}
\]  

(19)

Substituting for the zener sensitivity,

\[
\frac{\partial V_{T+}}{\partial T} = -(0.26 + \frac{R_7}{R_7 + R_8}) * \frac{\partial V_{BE}}{\partial T}
\]  

(20)

This term will always be negative irregardless of the values of \( R_7 \) and \( R_8 \) in equation (20). Therefore, it is now possible to adjust the ratio of \( R_5 \) to \( R_6 \) to achieve a
condition of voltage insensitivity to temperature. In other words, when R5 and R6 of figure 1.9 have been set to establish the upper clipping threshold, R7 and R8 may be adjusted to eliminate temperature effects. The actual relationship between the resistors R5, R6, R7, and R8 can be found from the following equation:

\[
V_{T+} = V_D + \left[ V_Z - V_{BE} - \left( \frac{R_7}{R_7 + R_8} \right) * V_{BE} \right] * \frac{R_6}{R_5 + R_6} + 2V_{BE}
\]  

(21)

The output sensitivity to temperature is therefore:

\[
\frac{\partial V_{T+}}{\partial T} = \left( \frac{R_6}{R_5 + R_6} \right) * \frac{\partial V_Z}{\partial T} - \left[ \left( 1 + \frac{R_7}{R_7 + R_8} \right) \right] * \\
\left( \frac{R_6}{R_5 + R_6} - 2 \right) * \frac{\partial V_{BE}}{\partial T}
\]  

(22)

Which, after substituting for the zener sensitivity, yields the following:

\[
\frac{\partial V_{T+}}{\partial T} = -\left[ \left( 2.26 + \frac{R_7}{R_7 + R_8} \right) \right] \left( \frac{R_6}{R_5 + R_6} - 2 \right) * \frac{\partial V_{BE}}{\partial T}
\]  

(23)

To achieve the desired result of temperature insensitivity, the multiplying factor on the partial derivative of \(V_{BE}\) is set equal to zero. On transposing the constant term this yields:

\[
\left( 2.26 + \frac{R_7}{R_7 + R_8} \right) * \left( \frac{R_6}{R_5 + R_6} \right) = 2
\]  

(24)

Finally, solving for R7 and R8 in terms of R5 and R6, the resulting balancing equation is:
\[ \frac{R_7}{R_7 + R_8} = 2 \cdot \frac{R_5 + R_6}{R_6} - 2.28 \] 

This completes the preliminary design of a dual range, double ended telemetry clipper.
CHAPTER 4

COMPUTER ANALYSIS

The design of the telemetry clipping circuit, as described in the previous chapters, has progressed to the point where a digital computer must be employed for complete performance analysis. Utilizing a rented computer service known as TYMSHARE\textsuperscript{12}, a detailed circuit simulation program has been run with the appropriate input data from the telemetry clipper schematics. The computer program chosen for circuit analysis was a "simulation program with integrated circuit emphasis", or, in short, SPICE. This code, written by L. W. Nagel and D. O. Pederson of the University of California\textsuperscript{13}, is a general purpose circuit simulation program. The procedures for selecting the circuit components and the simulation output results will be presented in this chapter.

Before deriving any of the resistor values, a few basic assumptions were made. First, the transistor Q9 in figure 1.9, as configured, was assumed to possess a zener break down voltage of 8.0 volts. This is realistic because it reflects the results of some actual laboratory measurements on 2N2222 NPN transistors. Secondly, an objective was set to try and keep the current drain down to \( \frac{1}{2} \) milliamp in each branch around the zener diode. These two
criteria established the minimum value for the combined resistances of R₁, R₂, and R₃ as:

\[ R₁ + R₂ + R₃ \geq \frac{V_Z}{0.0005} = \frac{8.0}{0.0005} = 16K \text{ ohms} \]  \hspace{1cm} (26)

Recalling the analysis of the previous chapter, under ideal conditions the lower threshold voltage tracks exactly the voltage of node "D" in figure 1.9. For Range I clipping (0.0 to +5.0 volts) this means that the potential of node "D" must be -0.5 volts. Resistor R₃ may now be found from the known voltage drop and desired current flow when terminal G₁ is grounded:

\[ R₃ = \frac{0.5}{0.0005} = 1K \text{ ohms} \]  \hspace{1cm} (27)

Switching the ground connection to terminal G₂, resistor R₂ may be found from the knowledge that node "D" must now be at a -3.0 volt potential. Solving for R₂:

\[ R₂ = \frac{3.0}{0.0005} - R₁ = 6K - 1K = 5K \text{ ohms} \]  \hspace{1cm} (28)

From equation (26), if the current is to remain at \( \frac{1}{2} \) milli-amp in this leg of the circuit, resistor R₁ must be:

\[ R₁ = 16K - R₂ - R₃ = 16K - 6K = 10K \text{ ohms} \]  \hspace{1cm} (29)

Resistor R₄ sets the current in the Q5-Q6-Q7-Q8 constant current source. This current is then duplicated in all the circuitry connected between the collectors of Q2 and Q4 in figure 1.9. The current through transistors Q9 and Q10 will be through the R₁-R₂-R₃ resistor bridge.
This has previously been established as \( \frac{1}{2} \) milliamp. If a total requirement of 0.7 milliamp is allowed, then \( R_4 \) may be determined. The \( V_{BE} \) voltage of \( Q_8 \) is approximated as 0.7 volts, and the current through \( R_4 \) is exactly half of that required, or 0.35 ma. Therefore, \( R_4 \) should be less than:

\[
R_4 \leq \frac{0.7}{0.00035} = 2K \text{ ohms} \quad (30)
\]

The current flowing through the section of the circuit consisting of \( Q_{11}, R_5, R_6, R_7, \) and \( R_8 \) must be made as small as possible to minimize total current requirements of the circuit. Recall that the potential difference between the upper and lower threshold voltages is exactly 6.0 volts, regardless of which range is being used. Subtracting off the \( V_{BE} \) voltages of \( Q_{16} \) and \( Q_{17} \), this means that the potential difference between the bases of these two transistors should be approximately 4.6 volts. Subtracting off the \( V_{BE} \) voltages of transistors \( Q_{14} \) and \( Q_{15} \), the potential difference between the bases of these two transistors should be approximately 3.2 volts. Finally, adding back the \( V_{BE} \) voltages of \( Q_{12} \) and \( Q_{13} \), the potential difference between the node "D" voltage and that of the base of \( Q_{14} \) should be 4.6 volts. Now, \( Q_9 \) has established an 8.0 volt difference between nodes "C" and "D" of figure 1.9. Subtracting the \( V_{BE} \) drop of \( Q_{10} \), this means that a 7.3 volt potential exists between node "D" and \( R_7 \).
Resistor R6 may be chosen as a moderately large value of 50K ohms. This sets the total resistance of the remainder of the branch as:

\[ R_5 + \frac{R_7}{R_7 + R_8} \cdot V_{BE} = \frac{(1.0 - 0.63) \cdot R_6}{0.63} = 29.3K \quad (31) \]

Choosing R5 as approximately half of that value yields 15K ohms. The ratio of R7 and R8 may be found through equation (25) from the previous chapter as:

\[ \frac{R_7}{R_7 + R_8} = 2 \cdot \frac{15K + 50K}{50K} - 2.28 \]

or,

\[ \frac{R_7}{R_7 + R_8} = 2.60 - 2.28 = 0.32 \quad (32) \]

The total combinatorial resistance of R5, R7, and R8 must not exceed 29.3K ohms from equation (31). R5 was selected as 15K ohms, therefore:

\[ R_7 + R_8 = 29.3K - 15K = 14.3K \text{ ohms} \quad (33) \]

Solving (32) and (33) simultaneously, resistor R7 must be selected as 4.6K and R8 will be 9.7K ohms.

The remaining resistors in the circuit present no analytical problems. R9 is provided merely to establish a bias voltage on transistor Q15. R10 and R11 likewise set the bias voltage for transistors Q16 and Q17, respectively. All three of these resistors may assume some large value on the order of 100K ohms. The final resistor, R12, prevents the overload of either transistor Q16 or Q17 from large
input voltages. A nominal value of 10K ohms will suffice for analysis.

Throughout the circuit synthesis an 8.0 volt DC input of either positive or negative polarity was attached to the clipper, and the output voltage monitored to four decimal places. The first cut component values used for the initial runs assumed a value of 0.7 volts for all $V_{BE}$ voltages. This, of course, is not the case in the true circuit, and, therefore, it was not surprising to find that the simulation thresholds were not exactly those predicted. Through several rounds of iterations, the resistor values were modified to achieve the desired thresholds.

Another feature of program SPICE was explored after the resistor values were corrected. Since junction transistors were now behaving according to equations (11) and (12) and not the approximation of equation (14), the operating temperature was changed. By running the program with the same data but at the extremes of the temperature range (-55°C and +125°C), instantaneous and accurate sensitivity analysis could be performed. The results of the simulation are shown in table 1.2, with a revised list of resistor values presented in table 1.3. It should be noted from table 1.2 that the circuit sensitivity is not entirely absent, but some small amount of drift is present. This is due to the fact that the resistor values have been rounded to the nearest 1000 ohm value (with the exception of R3). Removing this restriction would decrease the drift.
### TABLE 1.2. Final Computer Simulation Results

<table>
<thead>
<tr>
<th>Threshold (U/L)</th>
<th>Temperature (°C)</th>
<th>Value (volts)</th>
<th>Delta Change (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>---Range I: -0.5 to +5.5 volts absolute---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>125</td>
<td>5.4953</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>-55</td>
<td>5.4810</td>
<td>+0.0143</td>
</tr>
<tr>
<td>L</td>
<td>125</td>
<td>-0.5213</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>-55</td>
<td>-0.4857</td>
<td>-0.0356</td>
</tr>
<tr>
<td>---Range II: -3.0 to +3.0 volts absolute---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>125</td>
<td>3.0033</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>-55</td>
<td>3.0416</td>
<td>-0.0383</td>
</tr>
<tr>
<td>L</td>
<td>125</td>
<td>-3.0446</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>-55</td>
<td>-3.0418</td>
<td>-0.0028</td>
</tr>
</tbody>
</table>

### TABLE 1.3. Circuit Resistor Values

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Computed Value</th>
<th>Revised Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>10K</td>
<td>15K</td>
</tr>
<tr>
<td>R2</td>
<td>5K</td>
<td>9K</td>
</tr>
<tr>
<td>R3</td>
<td>1K</td>
<td>1.2K</td>
</tr>
<tr>
<td>R4</td>
<td>2K</td>
<td>2K</td>
</tr>
<tr>
<td>R5</td>
<td>15K</td>
<td>15K</td>
</tr>
<tr>
<td>R6</td>
<td>50K</td>
<td>42K</td>
</tr>
<tr>
<td>R7</td>
<td>4.6K</td>
<td>15K</td>
</tr>
<tr>
<td>R8</td>
<td>9.7K</td>
<td>10K</td>
</tr>
<tr>
<td>R9</td>
<td>100K</td>
<td>100K</td>
</tr>
<tr>
<td>R10</td>
<td>100K</td>
<td>100K</td>
</tr>
<tr>
<td>R11</td>
<td>100K</td>
<td>100K</td>
</tr>
<tr>
<td>R12</td>
<td>10K</td>
<td>10K</td>
</tr>
</tbody>
</table>
CHAPTER 5

BREADBOARD TEST AND EVALUATION

A final check of the circuit design is to hardwire a sample circuit and evaluate the operational characteristics over a wide range of simulated environmental conditions. This chapter addresses itself to the test and evaluation of that hardwired circuit. A detailed test plan has been developed, the response of the circuit to both a DC and a sinusoidal excitation has been observed, and a complete evaluation of the results reported.

The basic test plan began with the breadboarding of the circuit shown in figure 1.9. To prevent thermal runaway, the transistor pairs Q1, Q2 and Q3, Q4 had to be matched. This forced the use of integrated circuit transistor packages in the construction of the constant current sources. For the NPN devices, an XR-101 IC was chosen. The additional transistors in the integrated circuit were used for Q7 and Q8 in figure 1.9. The PNP array was implemented with an XR-102 package, the extra transistors being used for Q5 and Q6 in the same schematic. The balance of the circuit was to be made up of 2N2222 and 2N2907 transistors, but at the time of circuit construction there was a severe shortage of 2N2222s. In place of some of them, another integrated circuit transistor package was
used. A CAJ083 array replaced transistors Q12, Q13, Q15, and Q17 of figure 1.9. The resistors were all chosen with a one percent tolerance to accurately match the calculated values.

The test procedure established for this project consisted of the systematic monitoring of the four threshold voltages at five different temperature settings of the oven and test chamber. Prior to conducting the tests all equipment was checked out for proper operation. The actual testing was designed and conducted as follows:

1. Connect the voltmeter to the power supplies and set the appropriate levels. V+ was chosen as +15 volts, V- as -15 volts, and the input signal as 8 volts DC. The polarity of the input signal was changeable by reversing the terminal connections.

2. Turn all equipment off and connect the circuit to the power supplies through the external extension connector cables.

3. Connect the voltmeter to the circuit output.

4. Insert the circuit in the oven or test chamber and seal the door.

5. Set the temperature level for testing and wait 45 minutes for the circuit to stabilize.

6. Connect the system ground to node G1 on the circuit board (through the external leads).
7. Energize the V+ and V- power supplies while monitoring the power supply meters for excessive current drain.

8. Energize the input signal power supply.

9. Read and record the output voltage.

10. Turn off the input signal power supply.

11. Reverse the input signal power supply leads.

12. Repeat steps 8 through 11.

13. Turn off the V+ and V- power supplies.

14. Connect the system ground to node G2 on the circuit (through the external leads).

15. Repeat steps 7 through 13.

16. Select a new temperature and repeat the entire process from step 5.

The measured voltages representing the four different clipping thresholds are presented in table 1.4. The measurements were made at -55°C in the Tenny Engineering test chamber, at +27°C outside of all environmental chambers, and at +80, +100, and +125°C in the Grieve-Hendry laboratory oven. The test was initially conducted at room temperature to verify the dual range clipping capability by simply changing the ground connection. The observed thresholds were surprisingly close to the predicted values, given the unusual assortment of semiconductor devices in the circuit.

The temperature sensitivity of the threshold voltages was observed by successive uniform heating and cooling of
TABLE 1.4.

Breadboard Test Results

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Range I</th>
<th></th>
<th>Range II</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VT+</td>
<td>VT-</td>
<td>VT+</td>
<td>VT-</td>
</tr>
<tr>
<td>-55</td>
<td>+5.349</td>
<td>-0.501</td>
<td>+2.757</td>
<td>-3.109</td>
</tr>
<tr>
<td>+27</td>
<td>+5.414</td>
<td>-0.483</td>
<td>+3.019</td>
<td>-2.893</td>
</tr>
<tr>
<td>+80</td>
<td>+5.473</td>
<td>-0.466</td>
<td>+3.216</td>
<td>-2.736</td>
</tr>
<tr>
<td>+100</td>
<td>+5.499</td>
<td>-0.458</td>
<td>+3.305</td>
<td>-2.664</td>
</tr>
<tr>
<td>+125</td>
<td>+5.520</td>
<td>-0.448</td>
<td>+3.408</td>
<td>-2.578</td>
</tr>
</tbody>
</table>
the circuit. This is where the variation in semiconductor properties became evident. Because of the mix of three different integrated circuits and two different discrete transistor types, the voltage thresholds experienced a higher level of sensitivity than anticipated. The $V_{BE}$ of the transistors ranged from 0.5 volts to a maximum of about 1.2 volts. The junction thermal sensitivities, governed by equation (13), varied accordingly, leading to the results of table 1.4.

To verify the ability of the circuit to handle sinusoidal input signals up to 200 KHz in frequency, a signal generator was connected to the input leads. By monitoring the output response on a Hewlett-Packard model 180A oscilloscope, any obvious distortion or signal degradation could be detected and analyzed. Clipping occurred as expected on both ranges for an eight volt peak-to-peak input sine wave. The response remained clean over the entire frequency spectrum.

Finally, the power supplies were varied from +15 volts for $V+$ and -15 volts for $V-$ to 10 volts each. No noticeable changes occurred in the output response, indicating that the constant current sources were functioning correctly in the circuit. The complete design had therefore been successfully verified through breadboard testing.
A general purpose telemetry clipping circuit has been designed and tested. A clipper is a limiter, or a device which constrains signal information to remain either below an upper voltage level, above a lower voltage level, or both at the same time. It is the latter type that was implemented in this project, with an added capability of dual range operation. Typically, telemetry signals are passed between either 0.0 and +5.0 volts or ±2.5 volts. This clipper will effectively protect electronic equipment designed to operate in either of these ranges without any changes in circuit components.

Among the many uses for this device are applications in all phases of the telemetry field. Potential hazards of channel crosstalk, transmitter distortion, recorder saturation, and general signal degradation may be avoided through proper implementation of the clipper. Input protection to VCOs and other signal conditioning equipment can be effected easily with the requirement of only two power supplies at either ±10 volts or ±15 volts. This advanced design overshadows previous methods of signal protection involving zener diodes.
Specifically included in the design requirements was the flexibility of changing ranges of clipping with a minimum change in circuit components. This limiter can modify its clipping pattern by simply changing the ground connection from one terminal to another. An efficient operation such as this may be realized through hand modification, relay action, or transistor logic switching. Further flexibility in design allows for the addition of several channels of parallel clipping of the same basic configuration, thus minimizing component requirements and total system cost.
REFERENCES


4. IBID.


PART II

HOLOGRAPHIC MODEL MATCHING
INTRODUCTION

This portion of the graduate project report centers around applying a new optical technique to the analysis of photographic film. The intent is to show how holography can be used to improve upon current methods of reducing film of missiles or aircraft in flight for physical distance and orientation data. The procedure presently followed integrates the image on the film with the image of a scale model of the photographed object through a superposition video matching scheme known as the Photo Data Analysis System. The methodology of operation, as outlined in chapter 1, is as follows: First, the image on the photographic film is picked up by a television camera and displayed on a video monitor. At the same time, an exact scale model replica of the photographed object is positioned in front of another television camera, and its image is superimposed on the same CRT display. Then the scale model is positioned in three linear degrees and oriented in yaw, pitch, and roll until its CRT image exactly matches that of the photographic film. When this has been accomplished, geometrical measurements are made from the model and transferred to punched computer cards. The cards, derived in this manner from an entire flight test operation, are submitted to a computer for first and second time derivative calculation, tabular printout, etc.
Holography is a method of creating a three-dimensional image of an object. Since the Photo Data Analysis System uses three-dimensional scale missile and aircraft models, this project was initiated to investigate replacing those models with holograms. A major part of this project, therefore, was to research the area of holography and study the feasibility of making this substitution. The concept of holography is discussed in detail in chapter 2.

Chapter 3 outlines the efforts of producing a hologram, while chapter 4 covers the feasibility of using a hologram in the Photo Data Analysis System. An alternate approach to applying holography to data reduction techniques is introduced in chapter 5 which could possibly provide a means for automating the system.
CHAPTER 1

PHOTO DATA ANALYSIS SYSTEM

The Photo Data Analysis System (PDAS) is an opto-electronic system designed to retrieve kinematic data from photographic film of objects in motion. Originally called the Film And Television Correlation Assessment Technique (FATCAT), the first generation PDAS was completed in 1969. The Naval Missile Center, now the Pacific Missile Test Center, used PDAS to derive position and attitude information of Naval aircraft in flight. The system at that time consisted of a motion picture projector and television camera, a scaled-down model of the aircraft, a model positioning system with three-degrees-of-freedom, and a second video camera mounted on a 60 foot camera track. Image mixing and matching was accomplished by using a control and display console.

A study was conducted in 1973 which indicated that PDAS could be used to retrieve store-separation information from motion picture film. Store-separation refers to the activity of a missile during the time between captive and free flight. Several factors, such as the design of the missile launcher and the velocity of the aircraft, influence the drop characteristics of the missile. The kinematics of the missile during store-separation can be
recorded in time sequenced photographs from a camera mounted on the aircraft, as depicted in figure 2.1. Then PDAS is used to determine the position and attitude of the missile by model matching techniques.

A series of second-generation modifications improved the versatility of PDAS to include data acquisition in six-degrees-of-freedom. This was accomplished by adding a three-axis, six-degrees-of-freedom model positioner, and a similar camera positioner. The current system, as shown in figure 2.2, gives accuracies of ±0.1 foot for position data and ±1.0 degree for attitude data.

The sequence for deriving kinematic data from a typical store-separation operation is illustrated in figure 2.3. A camera is mounted on the aircraft and adjusted to fit the aircraft's coordinate system. The flight test is conducted next, a movie is made of the store-separation, and the developed film is delivered to PDAS. Here it is edited for exact time of firing. This establishes the time reference point. A scale model of the missile is mounted in the three-axis, six-degrees-of-freedom model positioner, and PDAS is calibrated for data reduction. The same lens that was used on the movie camera in flight is placed on the model video camera to eliminate any distortion which might be introduced from lens effects.

Now the superposition process begins. One frame of the movie film is displayed on the monitor. At the same time, the image of the missile model is projected on the
FIGURE 2.1. Missile Store-Separation
FIGURE 2.2. The Photo Data Analysis System
Mount Cameras on Aircraft

Survey Cameras into Aircraft Coordinate System

Flight Test Separation of Store

Edit Film for Time

Calibrate PDAS

Mount Model

Extract Six-degree-of-freedom Data by Superposition

Punch Data on Cards

Computer Time Correlations
Transform Coordinates
First and Second Time Derivatives
Smoothing and Curve Fitting
Tabular Printout
Graphic display Versus Time

Kinematic Output

FIGURE 2.3. Steps in Kinematic Reduction
monitor by video mixing. An operator adjusts the position of the missile model until its image coincides with the image on the movie film. Then the scaled coordinates of the model positioner are recorded on computer cards. The location of the model relative to the television camera is proportional to the location of the actual missile relative to the original movie camera. Thus, the position of the actual missile has been determined.

Once the operator has triggered the PDAS to record the coordinate information, he can advance the film to the next frame. Then the operator repeats the image matching process. When they match, he punches out another computer card. After all of the film has been analyzed frame by frame, the resulting deck of keypunched cards is processed by an IBM-7094 computer. The data is smoothed by a 5-point fourth-degree polynomial derivative subroutine to find missile velocity and acceleration. Roll, pitch, and yaw rates can be calculated and displayed graphically or in tabular form. The entire process can be completed within two days after the film has been delivered to the PDAS operator.

Interest in holography as applied to PDAS has developed from a desire to reduce the costs of the system. An immediate return can be realized by replacing the cost of constructing a scale model with the lower cost of creating a hologram. A scale model is expensive because it must be visually identical to the real missile, only
scaled in size. It must also be designed to fit the specialized three-axis, six-degrees-of-freedom model positioner to allow the pitching and body rolling movements necessary for image matching. Currently the missile models are machined of aluminum to a tolerance of 0.005 inch. The one time development cost runs in the hundreds of dollars. In contrast, a hologram of an actual missile can be made for a materials and labor charge of around $25 per copy. If the missile that is used in the flight test is also used for the hologram, there are no tolerances involved.
CHAPTER 2

HOLOGRAPHY

Holography was developed in 1948 by Dr. Dennis Gabor as a method of improving the resolution of the electron microscope\(^2\). Experimental holography was hampered by the lack of a highly coherent light source, and interest in holography declined in the early 1950's. After the development of the laser in July 1960, holography was reintroduced by E. N. Leith and J. Upatnieks\(^3\). Since then both theoretical and applications research have progressed steadily.

The concept of holography can best be described as the freezing of light waves in time. The light reflected from an object which has been illuminated by coherent laser light is "frozen" as a wavefront on the surface of the hologram. Then when coherent light passes through the hologram, the original wavefront is reconstructed and continues on its path as if it had just come from the object. Viewing the reconstructed wavefront gives the illusion that the object is physically present in the position it occupied when the hologram was created.

The term hologram comes from the Greek roots holo (complete) and gram (picture). The "complete picture" is achieved through a process similar to photography.
Recording the object wave rather than the object image is the basic difference between holography and photography. Because of this, the hologram can not be viewed directly like one would view a photograph. A hologram must be treated as a window. By looking through the hologram, rather than at it, the image of an object will appear in true three-dimensional perspective. This phenomenon is achieved by not only capturing the amplitude intensity, or irradiance distribution, of an image as in photography, but also the phase relationship of the propagating object wave itself. Photographic emulsions are sensitive to amplitude variations in light waves, but are insensitive to phase variations. Thus, to record phase information, the phase variations must be converted to amplitude variations. The conversion can be accomplished through recording the interference patterns generated from the interaction of a reference wave with the object wave

This interaction can be recorded only if the interference patterns are stable in time. To accomplish this a coherent monochromatic light source, such as a laser, illuminates both the object and the photographic plate. A gas laser with a long beam coherence length can be used to produce the interference fringes while offering the necessary small source size.

Holography requires a small monochromatic light source to insure spatial coherence. The coherence of the illumination depends on the dimensions of the source. As the
size of the source is increased the sharp interference fringes produced on the photographic emulsion become less pronounced. The hologram, when viewed later, will experience a loss of resolution, or efficiency. The reconstruction efficiency is the ratio between the amount of power diffracted or projected into the viewed image and the total amount of power in the incident beam striking the hologram. The brightness of the reconstructed image is important because the eye usually judges the quality of a reconstruction by the brightness of the projected image. Thus, high efficiency is an important requirement for visual holographic applications.

Holography consists of two basic stages. In the recording stage the complex information contained in the object wave is recorded on some storage medium, usually photographic film. In the viewing stage this object is reconstructed by illumination. The typical optics arrangement for hologram recording is shown in figure 2.4. The components of the system will be discussed in a subsequent chapter. The key point to be made here is that the object wave and reference wave are interfering with each other on the surface of the film. The system must permit the recording of the resultant fringe pattern.

In order for the recording to be made it is required that the fringe patterns remain stationary during the exposure period. Only a very small amount of motion can be tolerated before the fringe pattern is washed out. As
FIGURE 2.4. Typical Hologram Recording Geometry

Scale: 1/4 inch equals 1 inch
a general rule, if the motion of the fringes is restricted to less than one eighth of their minimum spacing, then a good recording can still be made. When a helium-neon laser with an output wavelength of 632.8 nm is used in a typical holographic recording situation, then the minimum fringe spacing will be approximately 1.2μ. Therefore, the allowable movement of the fringes will be one eighth of this, or 0.15μ.

Fringe patterns can shift because of film movement or a change in the length of one or both of the illuminating waves. In the direction perpendicular to the bisector of the shear angle, or angle between the reference and signal waves, the film movement must be less than one eighth of the fringe spacing. Again, for a helium-neon laser application this is approximately 0.15μ. All other film movements are less critically restricted. A change in the path length can be attributed to vibration of the optical elements in the system, or a change in the index of refraction of the air along the path length. The allowable physical movement of any one of the optical elements in the system is on the order of 0.05μ. Changes in the index of refraction are similarly restricted. According to J. Upalnieks, a 0.3°F change in temperature or a 0.05mm-Hg change in pressure over a path distance of one meter will change the index of refraction and deflect the affected wave far enough to wash out the hologram. These restrictions are summerized in table 2-1.
TABLE 2.1

Holographic Recording Tolerances

<table>
<thead>
<tr>
<th>Variable</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film movement</td>
<td>0.15μ</td>
</tr>
<tr>
<td>Optical element movement</td>
<td>0.05μ</td>
</tr>
<tr>
<td>Local temperature change</td>
<td>0.31°F</td>
</tr>
<tr>
<td>Local pressure change</td>
<td>0.05mm-Hg</td>
</tr>
</tbody>
</table>

The restrictions outlined in table 2.1 can not be exceeded for long at any time during the recording process. Thus, to produce accurate holograms the environmental conditions must be stable, or the exposure time must be very short. Fine grain high resolution film is inherently slow. It requires exposure times on the order of seconds. Therefore, the environmental conditions must be controlled to within the tolerances of table 2.1.
CHAPTER 3
HOLOGRAM RECORDING

Holography is a new field, and there are very few schools offering formal courses in the subject. Since a major part of this project involved learning about holography, a program was initiated to investigate holography via an experimental approach. It was found that the exercise of setting up a recording laboratory provided the necessary background information on the entire holographic process. The results and experience gained in this endeavor are presented in this chapter.

A holographic recording laboratory consists of many pieces of equipment, the most important of which is the laser. A laser provides the necessary coherent, monochromatic light source for holography. The coherence length of the particular laser used limits the maximum size of the object from which a hologram can be recorded. This coherence length is commonly defined as the point at which the visibility of the fringe patterns in a Michelson interferometer drops to one half of the maximum visibility. In this case the visibility is given as the difference between the maximum and minimum fringe intensities divided by the sum of the two. The illumination intensity of a fringe pattern is a measure of the quantity of light passed.
The intensity of the laser is also important in good quality holography. High-power lasers are desirable because they help reduce the time required to expose the film. The higher the power of the laser, the shorter the period over which the environmental tolerances, such as temperature, pressure, and vibration, must be maintained. High-power lasers can not yet be obtained, however, without a decrease in the coherence length. It is necessary, therefore, to achieve the proper match of coherence length to laser power.

A Spectra Physics model 120 helium-neon continuous wave gas laser was available for experimentation in holography. This particular laser has been recommended for holography of small objects because of its 8 inch coherence length and safe power level of 5 milliwatts. The main lasing frequency is 632.8nm, which is in the red region of the visible spectrum.

The beam guiding elements of the system, the mirrors and beam splitter, were high quality optical components. Any defects in these elements will distort the wavefronts before they hit the photographic plate. This is not serious if the same distortions are present when the developed hologram is illuminated for viewing. However, if a different reconstruction system is used, the resultant image will be distorted where the illuminating reference beam does not match the recording reference beam. It is much easier to record with low beam distortion from high
quality optical elements than to try to match the recording distortions upon reconstruction. A complete set of beam splitters was found which was more than adequate for holographic applications. Two optically flat first-surface mirrors of high reflectivity were also used in the recording process.

The output of a laser is a very thin beam of light with small divergence. Yet the subject to be illuminated and the photographic film are much larger. In order to bathe these elements in laser light, the laser beam must be diverged. A common method to do this is pictured in figure 2.4 where a microscope objective, configured with a pinhole as a spatial filter, is placed on the front of the laser. Microscope objectives have very short focal lengths which allows them to expand the laser beam in the required short distance. At the same time, the entrance aperture is large enough to fully accept the laser beam. Because they are highly corrected lenses, they expand the beam into a spherical wave. The spherical quality of the diverging beam is critical for uniform illumination.

The actual intensity distribution in a laser beam depends on the structure of its traverse mode. Further, the coherence properties are tied to the laser's oscillation mode-structure. A comprehensive review of this mode-structure can be found in Kogelnik and Li. So far as holography is concerned, the radiation from a laser oscillating in any one transverse mode is spatially
coherent. It is desirable that the fundamental mode of oscillation be the lowest order mode, the TEM$_{00}$, since more uniform illumination can be obtained from this mode than from higher order modes. This is because the intensity in all but the lowest order mode will vanish at different places along the laser beam. Thus, there is a nonuniform intensity distribution at any cross-section of the laser beam when higher order transverse modes are present. By bringing the beam to a sharp focus with the microscope objective, all the lowest order transverse mode wavelets will pass through one focal point. Placing a very fine pinhole at that point allows only the TEM$_{00}$ components of the beam to pass through by spatial frequency filtering. All other modes, as well as any distortion introduced by the microscope objective are not focused at the same point, and are thus blocked by the pinhole apparatus. The wavefront, after passing through the pinhole, will be spherical and follow a smooth Gaussian distribution. One drawback is that the beam begins diverging immediately after leaving the filter. Because of this divergence, short distances were required between the optical elements to efficiently utilize the object and reference beams in recording. These distances are depicted in figure 2.4 which has been drawn to one quarter scale.

Two forms of holography were attempted, and for this two different objects, or subjects, were required. The first type, known as Fresnel In-Line Holography$^{11}$ is
specialized in that the signal and reference beams are traversing the same paths. The signal beam in figure 2.4 was blocked out just past the beam splitter leaving just the reference beam. A semicircular plastic rod was used as the subject, and placed in front of the photographic plate in the path of the reference beam. The theory is that part of the incident beam passes undeviated through the translucent object to form the reference beam while the rest is diffracted by the rod and forms the signal beam. The two beams then interfere at the film plane and the interference pattern is recorded. The beams are following essentially the same path, so the shear angle between them is small. This results in wider fringe spacing and less stringent recording tolerances.

A more sophisticated holographic recording procedure allows for the use of opaque objects. It is known as the Fresnel Two-Beam Off-Axis method\(^{12}\), and follows the geometry of figure 2.4. The object chosen for initial hologram experimentation with this technique was a two-dimensional white statue of a comic character, selected for its high contrast ratio between the white surface and black background. Its easily recognizable form would assist in recognition in the event the holographic quality were poor but still detectable.

To activate the system, an electronic shutter was placed in front of the laser between the microscope objective and the beam splitter. With this shutter the
exposure time could be adjusted from 0.001 seconds up to 9.9 seconds. A Vincent Associates Uniblitz model 300 shutter timer control provided this flexibility.

The final element of any holographic system is the recording medium. For optical holography high resolution film is required. Two different types were chosen for this application. Polaroid type PN55 self developing film offered rapid turn-around time for system calibration. For sharper images Kodak type 649F spectroscopic plates were obtained. The anticipated recording process was to first use the Polaroid film with varying exposure times. After exposure the film would be developed and run under tap water in a sink to fix the development. Then the negative would be inserted back in the recording system. By blocking out the object beam at the beam splitter, the negative could be illuminated by the reference beam alone. When viewing the hologram the image of the object should appear superimposed with the actual object. Once this image is obtained, the recording system has been calibrated in terms of beam path lengths and intensities. Then the more expensive glass plates can be substituted for the Polaroid film. These high resolution plates require a longer exposure time, but if the environment is stable, the exposure time should be the only variable changed.

Initial set-up of the recording system was done with the use of a long piece of string and a light meter. The string was used to trace out the length of both the object
and reference waves. The exact path length is not critical, as long as the two beams travel the same distance. This was verified by measuring with the string. The light meter was used to select the appropriate beam splitter for the system. The fringe patterns formed on the film represent the modulation of the reference beam by the signal beam. For most effective results the lightest fringes should not be clear, but a very light grey. Likewise, the dark fringes should not render the film opaque, but tint it dark grey. The proper beam intensity mix will automatically provide this result. Experience of other experimenters has dictated that the ratio of the reference beam intensity to the subject beam intensity should be $3:1^{13}$, although results can be obtained using intensity ratios from 1:1 to 1:10. A beam splitter was selected so that a 3:1 ratio was measured at the surface of the photographic plate.

With the recording system set-up as explained, experimentation began using the Fresnel In-Line Holography technique. This approach is simpler than the side-band technique, and significant results were obtained without difficulty. Initial exposure times of 20 seconds were much too long. After attempting recordings at 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.06, and 0.04 second exposure times, the hologram made with a 0.1 second exposure reproduced the clearest image. Upon illumination two diffracted images of the laser source appeared as bright points through the
film. The points were seen above and below the actual laser source image. As the hologram was moved up and down, the point images moved either closer or further from the laser source image. If the film was moved far enough, the light diffracted from the side edge of the rod created a streaking image. The point source images remained, but a short tail appeared flowing from one point in the direction opposite to the closest upper or lower edge of the film. No images appeared beyond a radius of about one inch from the central laser source image. Since the rod was horizontal during recording, lateral movement of the film had no effect on the images. The other holograms with similar exposure times reconstructed the same images, only less pronounced.

Converting the in-line holographic set-up to a Fresnel Two-Beam Off-Axis recording laboratory involved replacing the plastic rod with an opaque object and removing the block from the signal beam of figure 2.4. The light intensity of the reference and signal beams was checked at the photographic plate to insure that the 3:1 ratio was maintained. Two recordings were made with the Polaroid film using exposure times of 0.08 second and 0.02 second. The fringe patterns in the latter were clearly present and appeared to be about the right intensity. Upon illumination, however, no images appeared for any orientation of the film. It was realized at this point that the resolution quality of the Polaroid film was too
low to record the fringe spacing associated with the larger shear angle between the reference and signal waves. With the set-up as pictured in figure 2.4, holograms could not be made simply by adjusting the exposure time as before. Further, the geometry of the optical components in the recording laboratory could not be changed since the reference beam was just passing by the edge of the object. In other words, the shear angle could not be decreased any further. The only viable solution to creating off-axis holograms was to increase the resolution quality of the film by using the Kodak glass plates. Unfortunately, the expiration date on the most recently available film was May, 1966, over ten years ago. For high resolution film considerable loss in quality can be expected beyond the expiration date. Thus, no attempt was made to use this film or set up the elaborate development requirements. Because of these limitations, no off-axis holograms were produced.

The purpose of this experiment was satisfied nonetheless. The exercise of setting up a holographic recording laboratory was meant to acquaint the author with the field of holography for which no formal background had previously been obtained. An appreciation was gained for the critical tolerances on temperature, pressure, and vibration required in holography, as well as the need for high quality optical components in recording. An understanding of coherence length and spatial filtering pointed out significant
features of holographic laser sources, and clarified the need to choose the proper laser for each holographic application. With this background it was now possible to investigate the feasibility of incorporating holography into the Photo Data Analysis System.
CHAPTER 4
PDAS HOLOGRAPHIC MODEL MATCHING

PDAS is used to reduce missile store-separation film. Any proposed modifications to the system should match or improve upon the measurement accuracy currently available. Since a hologram would be used to replace the scale missile model, the holographic image must be of comparable quality to that obtained from the actual model. The image matching will be conducted by an operator viewing a video monitor. Therefore, the visual requirements of that operator must be determined.

The two video images on the display must provide adequate contrast for the operator to detect and recognize significant features of the images. Johnson's Criteria specifies the minimum video resolution acceptable for feature detection and recognition.\(^{14}\) It states that two TV lines of limiting system resolution are required for a 50 percent probability of detection, and six lines are needed for a 50 percent probability of image recognition. The detailed matching of distinctive features of the images is the main criterion for model positioning. The detection of these features is critical. Therefore, the resolution quality of the hologram must be such that the clarity and sharpness of the image exceeds two TV lines.
To meet this requirement the brightness of the holographic image must be above a certain minimum level. This level can be specified in terms of an image contrast ratio. The minimum detectable contrast of an image to its background, known as the modulation contrast of limiting resolution, has been found to be two percent.\textsuperscript{15} For this to be achieved, the image contrast modulation must be around six percent for a typical display brightness of four percent. As the image contrast modulation increases, the clarity requirement of the image features becomes easier to meet.

A video recording system was obtained to verify that holography could conform to the video constraints. A hologram depicting a series of dominoes in a row was illuminated by a helium-neon laser, and a recording was made of the image. The picture quality met the requirements in brightness and clarity, as well as Johnson's Criteria.

Another consideration in using holography in PDAS is the ability to position the holographic image in six-degrees-of-freedom for video image matching. While video tape recording the holographic display of the dominoes, several maneuvers were attempted. First, both horizontal and vertical positioning were changed by moving the hologram left to right and up and down. The dominoes remained the same size and shape, but changed position on the video monitor. This correlates to X and Z axis
positioning in the coordinate system of PDAS. Moving the hologram closer to the TV camera increased the image size on the video display indicating a Y axis, or range change. The depth of focus of the hologram was observed by changing the camera focus. When the closest domino in the hologram was in focus, the furthest one was blurred. Bringing the back one to focus caused the image of the closest one to become blurred, thus demonstrating the three-dimensional quality of holography.

Positioning within the attitude orientations of yaw, pitch, and roll could not be effectively demonstrated with the domino hologram. This is because the orientation of an object when a hologram is made remains the same when it is illuminated. Moving a hologram in a plane parallel or perpendicular to a TV camera changes the linear position of the object, and moderately changes the attitude orientation relative to the camera within the constraints of the holographic window. This does not indicate direct control of the yaw, pitch, or roll, however. It was demonstrated that turning or tilting the domino hologram introduced image distortion rather than a yaw or pitch change. Pivoting the hologram gave a roll effect over small angles, but the roll was about the center of the hologram, not the object itself. Therefore, for a flat holographic plate, positioning can occur only in the three linear directions with a slight amount of attitude control.
If cylindrical holograms\textsuperscript{16} are used instead, two of the three attitude orientations can be varied under certain conditions. This was demonstrated using a hologram of a die. If the center of the object lies along the center axis of the cylinder, then the object roll can be simulated, as was shown with the dice cube, by rotating the hologram. Otherwise, the drawbacks of the flat hologram result where the object image does not pivot about its own axis. Depending on the orientation of the hologram, the yaw or pitch, but not both, can be controlled. Image distortion will occur if the holographic cylinder is turned such that the ends of the cylinder are not perpendicular to the image plane of the camera.

The only true way to achieve six-degrees-of-freedom is with spherical holography. Unfortunately, there has been no reported success with this difficult procedure. However, if two cylindrical holograms are created of the same object along perpendicular center axes, or at least six flat holograms are taken on each side of a cube surrounding the object, then the three attitude positions can be determined by superposition.

Even if PDAS image matching can be accomplished using holography, optical distortion can degrade the image of the object so that erroneous position data results. If the exact distance between the hologram and the laser point source is not the same in reconstruction as it was in recording, the image will appear either larger or smaller
than it should. The longitudinal change in this situation is proportional to the square of the lateral change. The problem can be corrected if the beam is colimated. Then the wavefront will propagate as a cylinder rather than a sphere, and the illumination separation distance will not be critical.

As mentioned before, if the hologram is turned or tilted so that the reference wave does not hit it at exactly the same slope and shear angle as it did in recording, complex distortions will result. The reconstructing optics of the holographic system must be alligned to prevent these large errors from being introduced.

In summary, it is possible to display and position a holographic image in X, Y, and Z coordinates on a video monitor. The image will show clarity and contrast comparable to the video image of an actual object. The attitude orientations of yaw, pitch, and roll can be simulated over a limited range, with best results obtained from cylindrical holograms and superposition analysis. Distortion of the image presents a real problem requiring a very accurate optical system and constant allignment.
CHAPTER 5

ADVANCED TECHNIQUES

An alternate method of advancing the capability of PDAS through holography has developed from research in the area of pattern recognition. Recall that the image of an object is seen through a hologram when it is illuminated by a spherical reference wave emanating from a point source. The key to holographic pattern recognition lies in the fact that the reverse is also true. That is, the reference wave will be recreated by the hologram when it is illuminated with light reflected from the object.\textsuperscript{19} Hence, a point source of light will be the "image" of the hologram illuminated by the object wave.

The point source image will be sharp only when the reconstructing object wave is the same as the recording object wave. If a hologram is made of a missile, then a sharp point will appear as the holographic image only when the missile is in the exact same orientation on illumination as it was in recording. Now, if the PDAS store-separation film is used as the object to illuminate a hologram that was previously recorded using an actual missile or missile model, a unique method of photographic data reduction will result. The hologram can be adjusted until it intercepts the light from the film at the same
orientation it encountered from the object wave of the actual missile during recording. At that time, the reconstructed reference wave will display a sharp point image. The position of the hologram when the point image is obtained can be used to determine the exact position of the missile relative to the aircraft coordinate system. An operator can derive angular and location information by noting the position of the hologram when the reconstructed reference wave point image is at a peak in clarity and brightness. Then the image on the film and the image encoded in the hologram are exactly matched, even though the operator is not actually viewing either one.

This technique looks promising for automating the PDAS system. The hologram could be mounted in a computer controlled three axis, six-degrees-of-freedom model positioner. The image of the reconstructed reference beam point source could be focused by a lens on a photo diode array. Since model matching is based on achieving the brightest and clearest image, the computer could adjust the model positioner while the photo diode array provided feedback on the image size and intensity. When the closed loop system indicated that no further adjustments by the computer would improve the image, then the position coordinates of the hologram would be transferred to a punched card or computer tape. The computer would check the output and advance the film. The next frame would be analyzed and the process would continue for the entire test.
A somewhat simpler application of holography could benefit PDAS in its current configuration by improving the quality of the film image through deblurring techniques. Film of store-separation operations may contain slightly blurred images due to several factors, such as motion, imperfections of the camera lens, atmospheric turbulence, or imperfect camera focus. A blurred photograph may be restored because the blurred information in the photograph does not irretrievably block out the true picture. The process of image sharpening has resulted from an extension of the basic holographic Fourier transform division method of G. W. Stroke and R. H. Zech. 20
REFERENCES


17. P. G. Lingenfelder, p. 22.

