WATER STATUS DETERMINATION BY
SENSING STEM DIAMETER IN COTTON PLANTS

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STATEMENT BY AUTHOR

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With love, to my son

Ricardo Diaz Campos
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ABSTRACT

It has been shown that the stem diameter in plants decreases proportionately with water stress. The objective of this thesis is the development of a method to continuously measure these changes under field conditions for extended periods of time.

The anatomy of the stem, the physical mechanism of gross water movement in the whole plant and an analysis of previous research are discussed.

The design of an electronic measuring system is presented along with field results. This measuring system was tested on cotton in 1979 and 1980 and yielded the changes in stem diameter before and after irrigation.
CHAPTER 1

INTRODUCTION

Purpose and Objectives

For years, irrigation schedules in cotton plants have been determined mainly by two methods: first, by experience obtained in innumerable observations of plant behavior when it is under water stress; and second, by indirect methods based on soil moisture measurements, typically using tensiometers. Both methods are indirect, and the success strongly depends on the ability or judgement of the person in charge. Recently, a new approach to determine the irrigation schedule has been devised. It is a direct method based on the measurement of the stem diameter variation of the plant when it is under water stress. The purpose of this thesis is to develop a system to sense the stem diameter variations in situ and explore the feasibility of this method to determine the minimal conditions needed to schedule an irrigation.

Brief Description of the System

In order to achieve our goal, a system has been developed to monitor the stem diameter variations during both the day and night. The system was designed to work under extreme environmental conditions like high temperature, humidity, rain and wind. It was also designed for low power consumption. The energy for the system operation was supplied
by batteries which were recharged by solar cells. A sketch of the electronics-plant system is given in Figure 1.

Besides the plant, the system can be subdivided into three well-defined parts:

1. The driving part. It provides the specific wave form to drive the sensing units.
2. The sensing unit. It is attached to the plant to sense the stem diameter variations.
3. The third part of the system is the demodulating section. It converts the sinusoidal signal from the sensing unit to a proper DC level.

The driving part consists of a very stable 10 KHz sinusoidal oscillator and an amplifier driver that amplifies the signal of the oscillator to a proper peak-to-peak amplitude level to drive the linear variable differential transformers (LVDT's) of the sensing unit. In addition, the amplifier is capable of providing enough current to drive twelve LVDT's at the same time. The gain is adjustable and the amplifier uses only one power supply.

The sensor part is composed of two parts: the LVDT and the housing. The LVDT is a linear differential transformer whose output voltage is linearly proportional to core movements. The LVDT core is moved by the plant stem so that any change in the stem diameter is sensed by the LVDT as an output voltage change. The resolution is in the order of several microns. The LVDT is attached to the stem by means of special housing with good stability against changes in temperature and
Figure 1. Block diagram of the system.
humidity. It provides the mechanical structure to adjust and keep the LVDT body attached to the stem regardless of environmental condition and stem growth.

Measuring the output voltage of the LVDT's presented two problems. First, not all types of voltmeters could read RMS values of sinusoidal signals in the order of 10 KHz with good linearity. Second, it was not possible to connect the LVDT output voltage to a data acquisition system that could not read signals with frequencies over 0.1 Hz. So to avoid these problems, a circuit was designed to demodulate the AC carrier signal and convert it to a DC signal that made the voltage measurement an easy task. Both the input and output signal of the LVDT were demodulated because both were used to evaluate the stem diameter variation.

The demodulator needed a negative power supply for proper operation, so a non-complicated DC-to-DC converter was designed to provide the negative voltage.

**Thesis Organization**

This discussion is divided into seven parts: introduction, background material, materials and methods, system calibration and test, field use, results, and conclusions and recommendations.

In the Introduction, the thesis objective will be stated and a brief description of the system will be given. Background Material will deal with the physiological organization of the plant, the physical mechanisms that influence the water transport, and the evidence of stem...
diameter variations when the plant is under water stress. Material and Methods deals with the specifications of the system, the placement of the LVDT's, and the housing specifications. The System Calibration section refers to calibration of LVDT versus displacement and temperature, and the gain test performed to the system. Plots of the results are included. Field Use includes a description of how to use the system in the field and how to mount and set the LVDT's for data acquisition. Typical data obtained by the system is shown. The Results chapter refers to the results obtained from the data analysis. The Conclusion and Recommendations deals with the problems associated with the sensor and the measurement technique, usefulness of the system, and recommendations for future research.

Besides the seven parts that form the thesis core, an appendix and bibliographic reference are included. Prints are included whenever it was necessary to clarify the discussion.
CHAPTER 2

BACKGROUND MATERIAL

Physiological

The plant body consists of morphologically recognizable units, the cells, each enclosed in its own cell wall and united with other cells, forming cell groupings named tissues, whose structure depends on the component cell and the type of attachment to each other. The arrangement of different tissues in the plant forms its major organs and reveals a definite structural and functional organization that performs the complicated plant functions.

Cell

Since Robert Hooke referred to cells for the first time in 1665, their structure and functions have been intensively investigated. Details of this work and detailed cell structure is not going to be covered here. There exist good references about plant cells, e.g., Esau (1977).

As an organic unit, the cell has a means of isolating its contents from the external environment. A membrane called the plasma membrane and the cell wall provides this isolation. A cell can release and transfer the energy necessary for growth and the metabolic processes. In addition, they can perform functions like synthesis of proteins, production of the reserve material and the hereditary role. These tasks...
are held in the cell by different organelles that constitute the cell. The principal organelles are the nucleus, cytoplasm, plastids, mitochondria, ribosomes, dictyosomes, microbodies, endoplasmic reticulum, lipid globules, ergastic substances, and vacuoles (see Figure 2).

**Nucleus.** As a deposition of genetic information, the nucleus plays a major role in cell division. It is surrounded by an envelope and contains one or more nuclei. The nucleolus shows a dense structure in which two kinds of elements, one granular, the other fibrillar, may be visible. Some of the granules contain ribonucleic acid (RNA). Smaller granules may contain protein. The fibrillar component is known to contain deoxyribonucleic acid (DNA), responsible for storage and transfer of information. Nucleoli shows small stained regions commonly referred to as vacuole that in living cells show a repeated contraction, a phenomenon that may be related to the synthesis of ribosomal RNA in the nucleus. A special kind of RNA known as the messenger RNA (M-RNA) is synthesized in the nucleus by transcription of DNA information. The message is carried out to the cytoplasm where it starts the synthesis of protein.

**Cytoplasm.** Surrounding the nucleus is the cytoplasm. It is a protoplasmic matrix constituted by the ground cytoplasm, and ribosomes, microtubules and membranes that are not parts of clearly circumscribed organelles (endoplasmic reticulum, microbodies, mitochondria, etc.). The ground cytoplasm contains proteins, lipids, nucleic acids, and other substances soluble in water. The cytoplasm is viscous and capable of forming a gel and is delimited from the cell wall by the plasmalema
Figure 2. "Typical" plant cell.
(a unit membrane) and from the vacuole by a membrane called the tonoplast. Embedded in the cytoplasm are the cell organelles. Their main functions will be described in the following paragraphs.

**Plastids.** Plastids are organelles that appear in many forms and sizes. They are characterized by their pigmentation. Plastids are involved in the photosynthesis process and storage of plant products such as starch, proteins, fats or combinations of these products. The principal categories of plastids are chloroplasts, chromoplasts and leucoplasts. Chloroplasts contain chlorophyll. They occur in green plants and are concerned with photosynthesis. Chromoplasts commonly contain yellow and orange pigments. They are found in flower petals, fruits and some roots. Leucoplasts, the non-pigmented plastids, are identified with young plastids. The plastids contain DNA and ribosomes and are considered genetically autonomous cell organelles.

**Mitochondria.** Mitochondria are organelles discernible as spheres and rods. They are concerned with protein anabolism and respiration. Mitochondria possess DNA and ribosomes, but their genetic capability is limited; so considering the mitochondria as an autonomous organelle is still under discussion.

**Ribosomes.** Ribosomes are small particles (170-230 Å in diameter) that are the sites of protein synthesis from amino acids. They are found in nuclei, plastids and mitochondria. Ribosomes contain about equal amounts of protein and RNA. During the protein synthesis, the amino acids are formed into united chains named polyribosomes by the genetic message carried in the RNA.
**Dictyosomes.** Dictyosomes are organelles composed of stacks of two to seven (sometimes more) flat circular cisternae, each bound by a unit membrane. The totality of dictyosomes in a given cell is known as Golgi apparatus. The main function of dictyosomes is concerned with secretion. The product to be secreted accumulates and is expelled out of the dictyosome in small spheres named vesicles which carry the material to its destination. The secreted product is not synthesized exclusively in the dictyosome, but may be derived from an outside source and condensed and transformed in the dictyosome. Dictyosome-derived vesicles are involved also in the initiation of a new cell wall after nuclear division.

**Microbodies.** Microbodies, also known as cytosomes, occur in a variety of plant species and tissues. They have a single bounding membrane and their matrix is granular or fibrillar. Microbodies contain enzymes that vary according to the type of cell. They perform functions as glycolate metabolism and lipid degradation.

**Endoplasmic Reticulum.** Endoplasmic reticulum (ER) is a complex membrane system with rough surface when ribosomes are adhered to it or a smooth surface in the absence of ribosomes. The endoplasmic reticulum has some relation to the cytoplasmic strands traversing the cell walls. This suggests that the ER may play the role of an intracellular circulatory system transporting sugars, amino acids, and adenosine triphosphate (ATP) to sites of usage and storage in the cell. The association of ribosomes with the ER is interpreted as evidence that the ER is also involved in protein synthesis.
Lipid Globules. Lipid globules are described either as organelles enclosed in a unit membrane or as lipid droplets having no bounding membrane. In most cases, the droplets are embedded in the cytoplasm and other organelles like plastids and mitochondria. Lipid globules have been identified as membrane-bound organelles in which hydrolases are associated with triglycerides.

Ergastic Substances. Ergastic substances are passive products of protoplast that occur in other organelles, cytoplasm, vacuoles and cell walls. They are starch grains (storage substances), proteins, tannins (a group of phenol derivatives), fats, oils, waxes, and crystals (as calcium oxalate).

Vacuoles. In contrast with animal cells, plant cells develop an internal aqueous phase, the vacuole, which is bound by a membrane called the tonoplast. The vacuole is an important component of plant protoplasm (protoplasmic and nonprotoplasmic single-cell content, except cell wall). It contains water and a variety of organic and inorganic substances, some of them in the dissolved state. They may be reserve compounds such as sugars, organic acids, proteins, or they may be excretory products such as calcium oxalate and tannin compounds. Vacuoles not only accumulate metabolic products but are part of the senescence and differentiation process and mobilization of reserves in the cell. The method by which the vacuole originates is not clear; but as the cell enlarges, the vacuoles enlarge also and fuse into a single large vacuole that occupies the central part of the cell.
Vacuoles play a very important role in uptake of water during germination and growth and maintenance of water in the cell. Because the tonoplast membrane enclosing the vacuole is permeable, it is involved in the regulation of osmotic phenomena associated with the different concentrations of minerals and sugars within the vacuole. Vacuoles are involved with the maintenance of turgor in the cell and consequently in the whole plant. Due to this property of vacuoles, plants may squeeze or swell, depending if they are under water stress or not.

Cell Wall. The cell wall is the last of the more important cell components to be mentioned here. It restricts the size and shape of the cell at maturity. The cell wall determines the texture of the tissues. In peripheral tissues, cell walls contain material that protect the cell from dessication. In some tissues, walls perform activities such as absorption, transpiration, translocation and secretion.

The principal compound of cell walls is a polysaccharide called cellulose that determines the cell wall architecture. This polysaccharide forms a framework of fibrils of different magnitude named microfibrils and macrofibrils that display a dense, textile-like pattern. During the cell wall growth process, microfibrils are arranged in successive increments, forming the wall layers that give a more or less rigidity to the membrane. This wall rigidity provides the mechanical support for plant organs.

Cell Types

Cells do not necessarily have all organelles mentioned before. Some of them are not part of mature cells; others are the principal cell
component. For example, some cells at maturity may lack protoplasts; others may be highly vacuolated or may have only thick elongated cell walls. These differences and the cell functions lead to a cell classification. The main cell types are parenchyma, collenchyma, sclerenchyma, tracheary cells and sieve elements. Obviously, this is not an exhaustive list of all cell types, but they are the principal types (see Esau, 1977).

Parenchyma. Parenchyma is the main representative of the ground tissue. It is a living cell forming continuous tissue in roots, cortex, pith of stem, petioles, leaves, and in the complex tissue system of xylem and phloem. The presence of complete protoplast in the cell during all life allows the parenchyma cell to perform numerous functions at the same time. Wound healing, regeneration, formation of adventitious roots and shoots, and union of grafts are some examples of these functions.

Parenchyma cells vary in form. They have a polyhedric form that is not much longer than wide and may be nearly isodiametric. Parenchyma cells have many faces which are in contact with neighboring cells, forming well-organized tissues. The arrangement of cells varies, depending on the type of tissue. For example, storage tissue has abundant intercellular spaces, but in seeds storage tissue is a compact tissue with small intercellular spaces, if any. Spaces are associated with the requirements for gaseous exchange in photosynthetic tissue. Another characteristic of parenchyma cells is that they are highly vasculated and form lacunated tissues found in leaves, cortex and phloem. These cells are highly related with the plant turgor and ultimately with stem diameter variations.
Collenchyma. Collenchyma cells are thick-walled and are regarded as supporting tissue. They have complete protoplasts, capable of resuming all functions of live cells. Collenchyma cells are similar to parenchyma except that collenchyma are longer and thicker. The thicker wall is the most distinctive characteristic of these cells. This cellulose wall thickening is deposited in several patterns while the cell is growing. It is rich in water and sometimes shows transverse and longitudinal microfibrils.

Collenchyma cells are distributed principally in the peripheral regions of the stem and leaves (roots rarely have collenchyma). The tissue is located beneath the epidermis, forming a continuous layer around the stem circumference or sometimes, in many herbaceous stems, it occurs in strands.

Sclerenchyma. Sclerenchyma cells may or may not retain their protoplasts at maturity. They have secondary walls that are deposited over the primary when the extension growth is completed. Mechanically, sclerenchyma cells are referred to as those that lend hardness or rigidity to tissues. They are divided in two categories, sclereids and fibers. Sclereids are widely distributed in the plant body and vary greatly in shape. These cells have thick secondary walls, strongly lignified and with numerous single pits. Sclereids occur in the epidermis, the ground tissue, the vascular tissue, leaves, fruits and seeds.

Like sclereids, fibers may be found in various parts of the plant, but are particularly common in the vascular tissues forming the
phloem fibers and in the xylem, forming wood fibers. These fibers are long cells with more or less thick secondary walls that occur in strands and serve as supporting elements in plant parts that are no longer elongating.

**Tracheary Elements.** The tracheary elements are the most highly specialized cells of the xylem. They are concerned with the water conduction. Tracheary cells are elongated and nonliving at maturity. Their walls are lignified with secondary thickening. There are two types of tracheary cells: the tracheids and the vessel members. The tracheids are longer than the vessels and do not have perforations for water conduction. Instead, the passage of water from cell to cell occurs mainly through pit (cavity in the cell wall not covered by secondary wall) pairs, in which the pit membrane is permeable to water and dissolved substances. In vessel members, the water passes freely through one or more cell wall perforations at each end of the interconnected members. Sometimes, water passes from one vessel to another through perforations on the cell wall sides.

During the early stages of tracheary cell growth and secondary wall deposition, the protoplast contains all organelles, including the nucleus; but after the secondary wall is deposited, the cell enters the stage characterized by an autodigestion process that removes the non-cellulosic components of the cell wall, leaving a fine network of microfibrils that will be the site of future perforations. At the same time, protoplasm is broken down and reabsorbed by the plant.
Sieve Elements. Sieve elements are highly specialized cells found in the conductive tissue of the phloem. Their principal characteristics are the restricted metabolic activity of protoplasts and the close connection with contiguous sieve elements through cell wall areas (sieve areas) penetrated by pores. These pores permit the interconnection of protoplasts between sieve cells.

The degree of specialization of the sieve areas and its different distribution in the wall of a given cell serve to classify the sieve elements into sieve cells and sieve tubes. In sieve cells, the cells are not highly specialized and are not markedly aggregated on restricted wall parts to form sieve plates. In sieve tubes, however, they have highly differentiated sieve areas with big holes interconnecting one cell to another, forming a continuous tube. Sieve tubes have developed a higher degree of specialization for longitudinal conduction than sieve cells. However, both sieve elements are connected longitudinally end-to-end to other elements to form functional conducting units named sieve tubes that are the principal part of the phloem tissues.

The cell types mentioned above are the principal components of the xylem and phloem tissues. Both xylem and phloem form a complicated tube network for water transport in the plant called the plant vascular system.

Vascular System

The primary vascular system of seed plants is composed of the xylem and phloem tissue. It consists of strands variable in size where discrete individual strands are commonly referred to as vascular bundles.
The phloem and xylem show variations in their relative position in vascular bundles. Phloem may occur on one side of the xylem or surrounding it. Sometimes the xylem surrounds the phloem. But whatever the bundle's relative position, xylem and phloem achieve the important function of plant liquids transport. A hypothetical model of the water movement in the vascular system is represented in Figure 3. Typical hydrostatic ($\psi$) and osmotic ($\pi$) pressure values are for a 10 m high plant.

Under usual conditions, essentially all the water entering a plant comes from the soil by way of the root. Water must cross the root epidermis, the cortex and then the endodermis to reach the root xylem. Water is then conducted by the xylem to other parts of the plant where dissolved minerals are anabolized during the photosynthesis process. In this process, water is lost by transpiration, producing a negative hydrostatic and osmotic pressure that, as we will see later, is the thing that promotes water movement from the soil to the plant.

The anabolized products must move out of the leaves to other parts of the plant such as roots, stems, young leaves, developing fruits, and flowers where they will be either metabolized or stored. These products move primarily through the specialized tissues of the well-organized tube network of the phloem. As in the xylem, hydrostatic and osmotic pressure gradients are responsible for the metabolic products' movement in the phloem. We will talk more about these gradients later.

Xylem. The xylem is the principal water-mineral conducting tissue in a vascular plant. It extends throughout the plant, including all
Figure 3. Hypothetical model of xylem and phloem flow. -- a. Typical plant flow; b. Flow model.
branches, stems, leaves and roots. Two types of tissues can be identified in the xylem. The primary tissue differentiates during the formation of the plant body, and the secondary is produced during the second major stage of plant development in which an increase in thickness results from lateral addition of new tissue. This secondary tissue became the non-functional hard cell wall that forms the plant wood, and this wood performs a very important function, namely, the plant support.

The principal cell types of the secondary xylem (secondary tissue) are the tracheary elements, fibers and parenchyma cells. Tracheary elements are concerned with the conduction of water and substances dissolved in water. They are elongated non-living cells at maturity with hard cell walls. The tracheary elements form the water-conduction-vessel bundles. The fibers are long cells with secondary walls, usually thicker than the walls in the tracheids. The fibers retain their protoplast at maturity and are concerned with storage of reserve materials. The parenchyma cells of the secondary xylem are represented by the axial parenchyma and the ray parenchyma. These two kinds of cell complexes are fundamentally alike regarding wall structure and contents. The parenchyma cells store starch, oils and many other ergastic substances.

The xylem shows the presence of two distinct systems of cells: the axial or longitudinal system, and the radial or ray system. The axial system contains cells or files of cells with their long axes oriented vertically in the stem or the root; that is, longitudinal to the main stem or branches. The radial system is composed of files of cells oriented horizontally with regard to the axis of stem or root (see
Figure 4). These two systems of cells provide water distribution in the plant.

The xylem is produced by meristemic cells that occupy a lateral position in the stem. These cells are called vascular cambium. Later the xylem cells undergo a process wherein they form the elongated cells with cellulose walls and lose their protoplasm at maturity. These dead elements with cellulose walls give considerable compression strength to the tubes and prevent them from collapsing under the extreme negative tension that often exists in the plant.

Phloem. The phloem is the food-conducting tissue of a seed plant. It is associated with xylem in the vascular system. Like the xylem, the phloem consists of several types of cells and may be classified, developmentally, into a primary and secondary tissue. The primary phloem is derived from meristemic cells at the time of formation of the primary plant, and the secondary phloem that originates in the vascular cambium tissue. The phloem tissue is less sclerified and less strong mechanically than the xylem tissue.

Primary and secondary phloem tissues contain the same category of cells. However, the secondary phloem is the only one organized in axial and radial tissues (see Figure 4). The principal phloem cells are sieve elements, sclerenchyma, parenchyma and companion cells. Sieve elements are highly specialized cells in the phloem. They have close connection with contiguous sieve elements through pores in the cell wall, and perform the long-distance conduction of food materials. Sclerenchyma fibers are common components of both primary and secondary phloem. They
Figure 4. Block diagram of secondary vascular tissue and its spatial distribution.
occur in the outermost part of the tissue and are part of the axial phloem. Sclerenchyma cells are concerned with storage of food materials and support. Parenchyma cells containing various ergastic substances, such as starches, tannins and crystals are regular components of the phloem. They are classified as radial and axial parenchyma cells. The axial cells may occur in parenchyma strands or as single fusiform parenchyma cells. The main activity of parenchyma cells is storage and radial translocation of food substances. Companion cells are more than likely specialized parenchyma cells with regard to the functional association with sieve elements regulating the translocation of food. Companion cells have relatively large nuclei and nucleoli, contain plastids, large mitochondria and endoplasmic reticulum. Most outstanding is the abundance of ribosomes and vacuoles in the cell.

The secondary phloem generated by the cambial tissue constitutes the innermost part of the bark. Compared with the secondary xylem, the secondary phloem constitutes a much less prominent part of branches, trunk and root because successive increments of the xylem accumulates in the branch, trunk or root whereas the old phloem is crushed.

Compared to xylem, phloem is not a rigid tissue but is rather considered a soft tissue. This makes sense because the cell components of the phloem are highly vacuolated and has little cell wall lignification. And although they do not collapse under the extreme negative hydrostatic and osmotic pressure developed in the plant, they undergo a small shrinkage. This shrinkage is proportional to the pressure gradient
in the plant that forces water in the vacuoles to move in or out of the cell.

Stem

The stem consists of three tissue systems, the vascular, the fundamental, and the dermal. The vascular system described in previous paragraphs is composed of the xylem and phloem tissues. The fundamental tissues are all tissues other than the vascular and dermal systems. The dermal tissues are formed by the dermis and epidermis, the latter providing the external stem protection layer.

The vascular system shows variation in the relative position of the xylem and phloem. The prevalent arrangement is collateral, in which the phloem occurs in one side of the xylem. The vascular bundles may be also concentric in which either the phloem surrounds the xylem or the xylem surrounds the phloem. The vascular system extends to leaves and branches with one or more vascular bundles that diverge from the cylinder of strands in the stem toward the leaves or branches. These extensions from the vascular system in the stem are referred to as traces. The branch traces extend through variable distances in the main stem, and all are connected to the main vascular system.

The fundamental system includes tissues other than the vascular and dermal tissues that, in a sense, form the ground substances of the plant but at the same time, shows various degrees of specialization. The main ground tissues are parenchyma in all its varieties, collenchyma and sclerenchyma. These cells form the pith, the intervascular region (pith ray) and the cambial tissue.
The pith is the ground tissue in the center of the stem while the pith ray is the tissue region located between the vascular bundles in the stem. The pith is commonly composed of parenchyma, which may contain chloroplasts. In many stems, the central part of the pith is destroyed during the plant growth. Frequently this destruction occurs only in the internodes (part of the stem where leaves or bundles are attached). Sometimes plates of tissue remain in the internodes. The pith has prominent intercellular spaces in the central part. The peripheral part has compactly arranged small cells with greater longevity.

Cambial tissue is a lateral meristemic tissue that produces the secondary vascular tissues. It occupies a lateral position in the stem and is a continuous sheath about the xylem of stem, roots and branches. The cells of the vascular cambium do not have dense cytoplasm.

Old cells have relatively few small vacuoles, but the active ones are highly vacuolated. Morphologically, these active cambial cells occur in two forms, called fusiform initial and ray initial. The fusiform initials and their derivatives constitute the axial vascular system, and the ray initials the radial system.

When cambial initials produce secondary xylem and phloem cells, they are produced at one time toward the xylem and at another time towards the phloem, although not necessarily in alternation. During this cambial activity period, cell additions occur so rapidly that older cells are still meristematic when new cells are produced by the initials. Thus, a wide zone of cell accumulation is formed. This soft cambial tissue zone is designated as the cambial zone.
Covering the vascular and fundamental tissues is the dermal system. This system is composed of the periderm and epiderm tissues. The periderm is a protective tissue of secondary origin replacing the epidermis in stems and roots that increase in thickness by growth. Periderm formation is also an important stage in the development of protective layers near injured or dead tissues resulting by mechanical wounding or invasion of parasites. The principal cell components of the periderm are the phellogen, the phellem and the phelloderm. The phellogen are meristemic cells that produce the periderm. They have only one form, rectangular and radially flattened cells.

The phellem is commonly called cork. The cork cells are characterized by having irregular form and arranged compactly with no intracellular spaces. The cells are in the outer part of the phellogen. At maturity, they are non-living cells but may have fluid or solid contents, some colorless, others pigmented. The main phellem function is to provide protection and isolation to the stem.

The phelloderm is the innermost tissue of the periderm. It is a living parenchyma tissue positioned in the same radial files as the phellem cells of stems and roots.

The other major tissue of the dermal system is the epidermis. The epidermis is a set of different cells in structure and function, that constitutes the cover of the plant body. The epidermis consists of a groundmass of unspecialized cells with specialized cells dispersed through the mass. Ground cells have living protoplasts and may store
plant products. Specialized epidermal cells are represented, first of all, by the guard cells of the stomata, by epidermal appendages called trichomes, and by cells containing tannins, oils and crystals.

LVDT-Stem Interface

During the course of the experiment, minimum damage to the plant and accurate measurements were desired. To minimize the plant damage due to attachment of the LVDT housing, two screw pairs with small contact areas (12.6 mm² each) at the tips were used. Each screw pair was tightened, one against the other, pressing the stem between them (see Figure 5). Good measurements were expected by placing the LVDT core at an angle of 90° with respect to the screws and halfway between both screw pairs, as we seen in Figure 5.

Using small contact areas at the screw tips, minimum mechanical injury and small constriction of the vessels of the plant were expected. Once the screws were set, they were left in the same position to the end of the season. The plant reacted to this invasion by developing a protective layer of peridermal tissue around the injured tissue and tried to engulf the screw tips (see Figure 5). At the end of the season (3 months), an average of 2 mm of peridermal tissue grew around the screw tips.

The core, the mobile part of the LVDT, was screwed to a fiberglass tip with big contact area (30.6 mm²) and placed at 90° with respect to the screws' plane. The vessels at this position were not touched by the screws, and they were not damaged. A small spring was used to keep the core tip pushing against the stem. Due to the big
Figure 5. LVDT housing screws and LVDT core spatial arrangement.
contact area of the tip, the spring force was uniformly distributed in a big surface, preventing the plant from damage. No peridermal tissue grew around the core tip.

In previous sections, the basic plant structure from the cellular level to the tissue level was developed. Water and minerals were found to be the fundamental components needed for plant growth. Furthermore, there exists a complete vascular system to carry these components to all parts of the plant. Now consideration will be given to the physical mechanisms that, without moving parts, force the water and dissolved minerals to move.

**Physical Water Transport Mechanism**

Whenever a plant grows, it faces water and mineral requirements. They must maintain a water and mineral balance with its surroundings. The dissolved substances (minerals) are in the soil and must be transported to the metabolizing plant that is in the atmosphere where leaves, during the photosynthesis process, exchange gases, absorb sunlight, and lose water by evaporation (transpiration). The energy required in this transport mechanism is supplied by the photosynthesis process.

**Free Energy and Chemical Potential**

Photosynthesis process converts the plentiful radiant energy from the sun into free energy needed to perform the biological work that keeps the plant alive. Lack of this free energy generation will lead the plant to energy equilibrium and eventually to death. The free energy generated during the photosynthesis process is stored in an
intermediate energy storage like ATP (adenosine triphosphate) that will bond to CO$_2$ and H$_2$O to form carbohydrates. This process brings the plant from stage "A" of lower energy to a stage "B" of higher energy and is reversed whenever the plant needs energy to perform a specific task.

The total free energy available is the superposition of the free energy per mole of each chemical component $j$ that changed its energy level from stage A to stage B. This quantity is called the chemical potential of species $j$ and is given the symbol $\mu_j$. During the transition from stage A to stage B, the element $j$ changes its chemical potential from $\mu^A_j$ to $\mu^B_j$ and the maximum amount of work that can be done per mole of species $j$ is $\mu^A_j - \mu^B_j$. This difference has an important role in discussing fluxes of element $j$ from one region to another. One can say that the chemical potential difference of element $j$ between two locations is the driving force for the movement of that element. Thus, the bigger the chemical potential difference, $\mu^A_j - \mu^B_j$, the larger the flux of species $j$ from region A to B.

The chemical potential of a substance mainly depends on its chemical composition, but it is also influenced by other factors such as hydrostatic pressure gradients, electric potential that affects the chemical potential of charged particles, and concentration gradients that produce movement of substances by diffusion. Finally, another contributor to chemical potential is the work performed against gravity that must be expended to move the substance $j$ upwards. An expression for the chemical potential of an element $j$ that takes into account all
of the above factors is given by the following equation (Nobel, 1974):

\[
\mu_j = \mu_j^* + \text{RTLna}_j + \overline{V}_j P + z_j FE + m_j gh
\]  

(1)

where \( \mu_j^* \) = reference level, \( \text{RTLna}_j \) = energy due to the solvent activity \( a_j \) (\( R \) = universal constant of gases, \( T \) = temperature in \( ^0\text{K} \)), \( \overline{V}_j P \) = effect of pressure on chemical potential (\( \overline{V} \) = partial molal volume, \( P \) = gauge pressure), \( Z_j FE \) = influence of electrical potential (\( Z_j \) = charge number, \( F \) = Faraday constant, \( E \) = electric field), \( m_j gh \) = potential energy (\( m \) = mass, \( a \) = gravity acceleration, \( h \) = height).

Water Potential

The focus of this investigation is with the water movement in plants; therefore one must examine what happens to the chemical potential equation if the element \( j \) is water. For this special case, the following assumptions were made.

\( w = j \); the subscript \( w \) refers to water
\( z_w FE = 0 \) (there is no electric charge in water)
\( \text{RTLna}_w = -\overline{V}_w \pi \); water activity per molal volume

Rearranging Equation 1, we get:

\[
\mu_w - \mu_w^* = \overline{V}_w P - \overline{V}_w \pi + m_w gh
\]  

(2)

The term \( \mu_w - \mu_w^* \) represents the work involved in moving one mole of water from some point in a system (at constant pressure and temperature) to a pool of pure water at atmospheric pressure and the same temperature. Both the system and pool are at the same level.
\[ \overline{V}_w P, \] in Equation 2, expresses the effect of pressure on the chemical potential of water. \( \overline{V}_w \) is the partial molal volume of water expressed in cm\(^3\)/mole. In the case of pure water \( \overline{V}_w = 18.0 \text{ cm}^3/\text{mole} \). \( P \) is the hydrostatic pressure of the aqueous solution in excess of the ambient atmospheric pressure. The units of \( P \) are bars (10\(^5\) N/m) or dimensionally equal to joules/cm\(^3\). Then the units of the product \( \overline{V}_w P \) are joules/mole.

The term \( -\overline{V}_w \pi \) expresses the effect due to the presence of solutes in an aqueous solution that tends to decrease the activity of water \( (a_w) \). When solutes are added to water, the concentration of water becomes less because the water molecules are displaced by those of the solute, lowering the chemical potential of water. \( \overline{V}_w \) is the partial molal volume of water expressed in cm\(^3\)/mole and \( \pi \) is the osmotic pressure in bars that depends on the presence of solutes.

To explain the term osmotic pressure, let us assume that one ideal membrane only permeable to water exists. When pure water is placed on one side of the membrane and some solution in the other, there exists a net diffusion of water toward the side with the solutes. To counteract this tendency and establish equilibrium, a hydrostatic pressure has to be applied to the solution side. This pressure is called the osmotic pressure, but is better known as the osmotic potential. In our case, an increase in the concentration of solutes raises the osmotic potential and decreases the water activity \( a_w \), so they change in opposite directions, giving a negative sign for the expression \( -\overline{V}_w \pi \) whose units are joules/mole.
The last term involved in the chemical potential of water is \( m_w g h \). This term expresses the influence of gravity on one mole of water when it is lifted to a height, \( h \). The units are joules/mole.

Now, if Equation 2 is divided by \( V_w \) we get:

\[
\frac{\mu_w - \mu_{w}^*}{V_w} = \psi = p - \pi + \rho_w g h
\]  

(3)

where

\[ \rho_w = \frac{m_w}{V_w} = \text{water density} \]

The left side of Equation 3 is well known as the water potential (represented by \( \psi \)). Its units are joules/cm\(^3\) or bars, which are units of pressure. We see from Equation 3 that the water potential in the plant depends only on three factors: the hydrostatic pressure, the osmotic potential, and the gravitational potential.

**Hydrostatic Pressure in the Plant.** In addition to being involved in the support of the plant, hydrostatic pressures are important for the movement of water and solutes in the xylem and probably also in the phloem. To predict in what direction water will move, one needs to know the water potential in the various compartments under consideration, e.g., pressures inside the tracheary elements, vacuoles and cytoplasm. For example, when water is in equilibrium across the vacuole membrane (tonoplast), the water potential is the same in the cytoplasm and the vacuole. In fact, the cytoplasm and the vacuole essentially have the same value of \( P \) (hydrostatic pressure) all the time.
Because the plant cells are highly vacuolated (they occupy about 90 percent of the total volume of the plant body), the vacuoles play an important role, providing large, relatively simple, compartments in which hydrostatic pressure leads to the cellular turgidity necessary for support of the plant. The hydrostatic pressure is transmitted to the vessel bundles of the xylem across the cell wall. As one may suspect, there exist different hydrostatic pressures between different organs of the plant. For example, typical values of hydrostatic pressure for a plant 10 m high are: 6 bars (1 bar = 10 newton/cm²) at the leaves and 5 bars at the roots. This difference produces a pressure gradient between the roots and leaves that forces the water to move.

**Osmotic Potential in the Plant.** For many purposes in plant physiology, it is convenient to relate osmotic potential directly to the concentration of solutes instead of expressing it in terms of water activity $a_w$. Any factor which influences either the water or solute content of a plant cell will have an effect on the magnitude of the osmotic potential of that plant cell.

The water content of the plant as a whole, and hence of its constituent cells, is controlled principally by the different rates of water loss by transpiration and water reabsorption. This process is influenced mainly by the water content in the soil. More negative osmotic potential is developed when the plant is growing under drought conditions than when it is growing with a favorable water supply.

The solute content of the cell sap is controlled by the specific metabolic processes of the plant and by absorption of mineral salts by
the plant from its environment. The photosynthesis is an important factor in influencing the osmotic potentials within the cells, particularly those of the leaf tissues. Increases in sugar content, resulting from the photosynthesis process, result in more negative osmotic potentials. Inherent metabolic processes affect the concentrations of the various types of soluble organic compounds present in cells, such as carbohydrates, organic acids and amino acids. Another factor involved is a decrease in the growth rate of the plant, which often permits an accumulation of mineral salts and soluble foods, creating a big negative osmotic potential.

Osmotic potential is the main component of the water potential because of its significant magnitude. Values of osmotic potential between -2 to -40 bars are common. In the same plant, different organs or tissues may differ widely from one to another in the osmotic potential of their cells. Leaf cells, for example, almost invariably are more negative in their osmotic potential than the root cells of the same plant. For a plant 10 m high, typical osmotic potential in the leaves is -17 bars and -9 bars at the roots. As one can see, this big difference in potential causes the water movement from the roots to the leaves.

Gravitational Potential. Gravity produces pressure due to the weight of the water column in the plant. Its effect is opposite to the water movement from the roots to the leaves. This effect becomes important only in high plants because a positive pressure of 1 bar is generated when a mole of water is lifted 10 meters. For small plants, like cotton, the gravity effect may be neglected.
Water Flux. When water potential inside a cell differs from that outside, the water is no longer in equilibrium and one can expect a water movement toward the region of lower water potential. Our attention here will be specifically focused on water flow into and out of plant cells. This volume flux of water, \( J_w \), is assumed to be proportional to the difference in water potential, \( \Delta \psi \), across the membrane or membranes restricting the flow. The proportionality factor indicating the permeability to water flow at the cellular level is expressed by a water conductivity coefficient, \( L_w \), then:

\[
J_w = L_w \Delta \psi = L_w (\psi^0 - \psi^i)
\]  

In Equation 4, \( J_w \) represents the average flux of water moving across the barrier being considered. \( \psi^0 \) is the water potential in the external solution, and \( \psi^i \) represents the water potential in the vacuole.

Now, if we generalize Equation 4 to the point in which \( \psi^0 \) and \( \psi^i \) are the water potential of the root and leaves, respectively, and \( L_{wt} = \sum_j 1/L_{wj} \) equal to the equivalent water conductivity when the series of all barriers from the leaves to the roots are considered, a good approximation for the water flow in the plant can be obtained:

\[
J_{wt} = L_{wt}(\psi_{\text{root}} - \psi_{\text{leaves}})
\]  

Typical values for the water flux are \( J_{wt} = 0.1 \) cm/sec in the xylem and \( L_{wt} \) about 0.005 cm/bar-sec.

We have already indicated that certain diurnal changes in the plant produce a water potential between the roots and leaves that forces
the water to overcome the resistance of the membranes to produce a water flux. We also indicated that when the rate of transpiration is high, the plant cannot take enough water from the soil; so the plant loses water from the vacuoles, thereby producing a high negative tension in the xylem, the phloem and companion tissue. Under this high tension, the hard non-vacuolated tissues of the xylem do not suffer an appreciable deformation; but the soft vacuolated tissues of the phloem, the companion tissue and cortex lose their turgidity, producing a slight decrease in diameter of the plant stem.

Stem diameter variation in plants is important because it is related to their water potential. In our case, our interest is in the stem diameter variation of cotton plants and its relationship to water stress. The following section is related to this problem.

### Previous Research on Stem Diameter Variation of Cotton Plants and its Relation to Water Stress

Water potential $\Psi$, is the best measure for the state of water in the plant. It depends on complex interactions between demands from the soil-plant-atmosphere system, but mainly on the rate of leaf transpiration and the rate of water absorption through the roots. When the soil is saturated the plant does not have any trouble compensating for the water loss by transpiration, but as the soil becomes dry there is not enough water uptake, then the plant uses water available in xylem vessels, phloem, cambial tissue, cortex and associated tissues to meet the demand created by the lag in absorption. Under this condition, a high negative water potential is developed in the leaves and because of
the good interconnection of leaves and xylem, approximately the same water potential change can be detected as plant stem diameter shrinkage due to a decrease of cell turgidity.

In cotton plants, the measurement of the stem diameter shrinkage and its relation to water stress has been extensively studied by researchers. Namken, Bartholic and Runkles (1969) and Klepper, Browning and Taylor (1971) performed experiments using LVDT's to continuously monitor the stem diameter variations in cotton plants during the day. They detached leaves periodically (generally hourly) and measured their water potential. They concluded that with a time lag, $T_p$, the stem variations followed very closely the water potential variations in the leaves (see Figure 6).

Molz and Klepper (1972) made an attempt to determine the relationship between the stem diameter variations in cotton plants and the water potential. They used a non-destructive technique based on the radial propagation of water potential in stems. Several assumptions concerning the stem and water potential were made: the xylem was considered as a continuous rigid ring with outer radius, $r_1$; the phloem and associated tissues as an external ring, concentric with the xylem, described the variable radius $r_2(t)$. Because of the relatively low resistance to water flow of the xylem vessel bundles, the water potential gradient in the xylem was considered sufficiently small such that the water potential gradient between the xylem and phloem is approximately equal in any part of the stem. Furthermore, the water flow velocity in
Figure 6. Diurnal change of cotton plant stem diameter and leaf water potential under wet and dry soil conditions. Notice the time lag, $T_p$ (Namken et al., 1969).
the phloem is assumed radial. The final assumption was that the stem
diameter contraction took place only in the phloem and associated tis-
sue. All these assumptions are summarized in Figure 7.

With such assumptions, Molz and Klepper (1972) obtained three
equations that relate the water potential at any radial distance, \(r\),
the cumulative volume of water flow per unit length and the stem dia-
meter.

\[
\frac{\partial \psi}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r D \frac{\partial \psi}{\partial r} \right)
\]

(6)

This is the Fick's second law for diffusion expressed in cylindrical
coordinates, and governs the water potential distribution in the phloem
and associated tissues.

\[
Q = - \int_{t_0}^{t} \left[ 2\pi r_1 D_w \frac{\partial \psi}{\partial r} \right]_{r=r_1} \, dt
\]

(7)

This equation represents the cumulative volume of water per
unit length across the xylem-phloem boundary. The flow direction depends on
the water potential value in the phloem with respect to the xylem.

The last equation of the three gives the stem diameter value.
If the volume of a unit length of the phloem at \(t_0\) is \(V(t_0)\) then at
any time \(t > t_0\), the phloem and companion tissue volume is given by:

\[
V(t) = V(t_0) + Q = \pi (r_2^2(t) - r_1^2)
\]

Then the stem diameter is:
Figure 7. Diagram illustrating assumptions in cotton plant water movement. -- a. Water flow to meet the water demand of leaves; b. Diffusion of water potential from xylem to phloem and associated tissues.
\[ S_d = 2r_2(t) = 2\left( \frac{V(t_o) + Q}{\pi} + r_1^2 \right)^{1/2} \]  

(8)

where:

- \( \Psi \) = water potential (bars) at any radial distance
- \( r \) = radial distance from the stem center (cm)
- \( t \) = time (sec)
- \( D \) = coefficient for diffusion of water potential (cm\(^2\)/sec)
- \( Q \) = cumulative volume of water flow per unit length (cm\(^3\) \cdot cm\(^{-1}\))
- \( t_o \) = initial time
- \( D_w \) = water self-diffusion coefficient relating water flow to water potential gradient (cm\(^2\)/bar \cdot sec)
- \( \frac{\partial \Psi}{\partial r} \bigg|_{r=r_1} \) = water potential gradient at the xylem-phloem boundary
- \( S_d \) = stem diameter (cm)
- \( V(t_o) \) = volume of phloem and related tissues at \( t_o \) (cm\(^3\)/cm)

To evaluate Equations 6, 7 and 8, Molz and Klepper used numerical methods and proper boundary conditions. The results for the predicted values of \( \Psi_L = \Psi \bigg|_{r=r_1} \), Q and Sd are in Figures 8a and 8b. On Figure 8a, one can see that the most negative water potential \( \Psi_L \) is reached about 12.30 hours while the maximum value for Q is reached 1-1/2 hours later. Using the computed values for \( \Psi_L \), Q and the ratio \( D_w = D/75 \), the theoretical stem diameter was evaluated for three different values of \( D \), as shown in Figure 8b. For \( D = 8 \times 10^{-7} \) cm\(^2\)/sec, the theoretical and measured values showed good agreement; thus there exists a good correlation between the stem diameter variation and the water potential.
Figure 8. Theoretical evaluation of water potential, $\Psi_L(t)$, cumulative flow, $Q$, and stem diameter variation, $S_d$. -- a. $\Psi_L(t)$ and $Q$; b. $S_d$ for different values of $D$ and $D_w = D/75$ (Molz and Klepper, 1972).
To prove that the stem diameter deformation is mainly due to the phloem variations, Molz and Klepper (1973) performed an experiment to determine the swelling percentage of the xylem and phloem. They forced the stem to shrink by drying the soil. A high negative water potential was developed (about 14 bars). When wilting symptoms became apparent, the soil-root system was saturated with distilled water, and the phloem and xylem swelling were measured. The results are shown in Figure 9.

Molz and Klepper (1973) found that the 92 percent of the stem variation had occurred in the phloem and only 8 percent in the xylem. This 8 percent was the upper bound because a few bits of phloem and cambial tissue were found between the measurement device and the xylem that could contribute significantly to the slight expansion recorded in the xylem.

Later Huck and Klepper (1977) proposed two methods to evaluate the water potential in cotton plants by measuring their stem diameter. The first method, called the "Shrinkage Modulus Method," involves determination of an arbitrarily calibrated shrinkage modulus, $w$, which relates a measured diameter change to a corresponding water potential, $\Psi(t)$, where:

$$\Psi(t) = \Psi(t_0) + \frac{\pi}{4} w [S_d^2(t) - IS_d^2(t)]$$  \hspace{1cm} (9)$$

and

$$w = \frac{\Psi(c) - \Psi(o)}{\frac{\pi}{4} [S_d^2(c) - IS_d^2(c)]}$$  \hspace{1cm} (10)$$
Figure 9. Diameter increase and relative contribution of xylem. -- Roots were saturated at $t = 0$ (Molz and Klepper, 1973).
where

\[ \psi(t) = \text{water potential at time } t \text{ (bars)} \]
\[ S_d(t) = \text{stem diameter (cm) at any arbitrary time } t \]
\[ IS_d(t) = \text{interpolated diameter (cm) at time } t \]
\[ \psi(o) = \text{water potential at equilibrium (bars) updated each time the system is recalibrated} \]

To evaluate the shrinkage modulus, two water potential readings are necessary, one at time \( t_o \) and another at \( t_C \) (about 6 hours later). \( \psi(t), S_c(t), IS_d(t) \) corresponds to water potential and stem diameter at \( t_C \).

The second method, called "Dynamic Flux Method," involves an iteration procedure which estimates the xylem water potential required to produce observed changes in the stem diameter.

Although both methods are simple, neither of them takes into account the time lag, \( T_p \), that elapses from the time the water potential in the xylem changes until it is sensed by a diameter variation in the stem. This may produce disagreement between the calculated water potential and the true one.

A method to determine the water potential in cotton plants that takes into account the time lag, was developed by So (1979). He made an analogy with the method to measure the soil water potential using tensiometers proposed by Klute and Gardner (1962), and assumed that the phloem and living tissues around the xylem have the same water potential \( \psi_p \). The equation obtained by So that relates the xylem and phloem
water potentials and takes into account the plant response time, is as follows:

$$\psi_L = \psi_X = \psi_p + T_p \frac{d\psi_p}{dt} \tag{11}$$

where

- $\psi_L = \text{leaf water potential (bars)}$
- $\psi_X = \text{xylem water potential (bars)}$
- $\psi_p = \text{phloem water potential (bars)}$
- $T_p = \text{plant's time constant (time lag) (hours)}$

The assumption is that $\psi_L = \psi_X$ is necessary to keep the analysis simple. In fact, this is a good assumption because as was stated by Slatyer (1967), "there appears to be a relatively little resistance to liquid flow through the xylem so the tension in the water is presumably approximately equivalent to the water potential in the leaves." Then Equation 11 can be written as follows:

$$\psi_L(t) = \psi_p(t) + T_p \frac{d\psi_p}{dS_d} \cdot \frac{dS_d}{dt} \tag{12}$$

where

- $S_d = 2r_2(t) = \text{stem diameter (cm) at time } t$
- $\frac{d\psi}{dS_d} = \text{"phloem sensitivity" (bars/cm)}$
- $\frac{dS_d}{dt} = \text{rate of stem diameter change (cm/sec)}$

So, assuming that the phloem tissue is fully elastic and that its volume changes are equal to the volume of water entering or
leaving the phloem tissues. This assumption of fully elastic material implies that:

\[
\frac{d\psi_p}{dQ} = C \tag{13}
\]

then the phloem tissue volume \(V(t)\) at time \(t\) is given by:

\[
V(t) = V(t_0) + Q \tag{14}
\]

Differentiating Equation 14 with respect to \(S_d\), we obtain:

\[
\frac{dV(t)}{dS_d} = \frac{dQ}{dS_d} \tag{15}
\]

Taking differentials of Equations 13 and 15, we obtain:

\[
d\psi_p = CdQ; \quad dV(t) = dQ
\]

then

\[
d\psi_p = CdV(t) \tag{16}
\]

Combining Equations 15 and 16, we get:

\[
\frac{d\psi_p}{dS_d} = \frac{dQ}{dS_d} \tag{17}
\]

To evaluate \(\frac{d\psi_p}{dS_d}\), two measurements of the leaf water potential must be done, one at predawn and the other about noon. Then,

\[
\frac{d\psi_p}{dS_d} = \frac{\psi_L(t_2) - \psi_L(t_1)}{S_d(t_2 + T_p) - S_d(t_1 + T_p)} = \frac{dQ}{dS_d} \tag{18}
\]
The last term to be evaluated before we use Equation 12 to find the water potential is the rate of stem diameter change, \( \frac{dS_d}{dt} \).

\[
\frac{dS_d}{dt} = \frac{\Delta S_d}{\Delta t} = \frac{S_d(t_1 + \Delta t) - S_d(t_1)}{(t_1 + \Delta t) - t_1}
\]  

(19)

The work presented in this section summarizes what has been done by other authors in the past. If we follow the chronological order of the publications analyzed here, one can see that at the beginning, it was necessary to cut leaves quite often and eventually kill the plant. Later, some efforts to find a "non-destructive" method to determine the plant water potential were conducted. However, even these "non-destructive" methods still have to be recalibrated daily by detaching one or two leaves. This calibration is a cumbersome task because it is necessary to use pressure chambers to evaluate the leaf water potential during calibration. At this point we may ask, can we develop a non-destructive, remote, continuous method to determine the water potential? This is the objective that we are trying to address. Our first step is the design of a system to constantly monitor the stem diameter in cotton plants.
CHAPTER 3

MATERIALS AND METHODS

System Specifications

The cotton plants we were working with were in the field growing as normal crops under production. The area used for most experiments was approximately 0.33 acres. This means that the stem-diameter measuring system had to work under extreme environmental conditions such as high temperature, different levels of humidity, rain and strong winds.

Low Power

Due to the nonavailability of electric power close to the cotton field, the system had to be operated with batteries recharged by solar cells. Thus, the system had to be designed for low power consumption.

Mechanical Mounting

It was decided to mount the integrated circuits of the system on a phenolic board using "wire-wrap" techniques. For mechanical strength and protection, the board had to be enclosed in a metallic box. Ideally, this box had to be placed as close to the plant under test as possible, but during irrigation this is not possible; so the box was placed on one side of the field and wires were run to the LVDT's through an underground conduit.
Temperature

If one considers that the ambient temperatures in southern Arizona during the summertime may vary between 11°C at dawn to 43°C in the afternoon, the temperature inside the metallic box will be approximately up to 60°C. The large temperature range inside the box required a careful electronic design to operate over the wide temperature range. Integrated circuits with military specifications were used.

Humidity

The humidity conditions in the canopy may vary, depending on the soil moisture. It can be up to 100 percent at irrigation and decreases to about 20 percent at the minimum. For the electronics inside the box, which is on one side of the field, humidity is not a problem; but for the sensor itself, which is attached to the plant stem, humidity can cause problems. Care in the selection of the housing building material and all mechanical parts was taken. Fiberglass epoxy, G10, with an insignificant dimension change due to humidity, was used for the housing body. Stainless steel springs and plated screws were selected. The LVDT itself is not a problem because it is built with non-corrosive materials.

Climate Variations

Strong winds and rains are part of the environment. Winds may bend the plant about ±45° from the vertical position. The only way to prevent undesired effects for this condition is an immovable attachment of the sensor housing to the plant.
LVDT's Range

From previous measurements of the stem diameter variations done in the past by several researchers, it was found that 300 μm is about the maximum stem diameter variation during the day. For our purpose, a Schaevitz LVDT model 025 MHR was selected. It is a lightweight LVDT (5.4 grams) with a linear range of ±635 μm from the center position.

Sampling Rate

If we go back to Figure 6, one can see that after the 1800 hours, the more pronounced slope occurs and lasts about 2 hours. During this time the slope is about 1.46 μm/min. A sampling rate of 15 minutes will be more than enough to detect the fastest variation that may occur in the stem.

LVDT Transducer and Driver Meter

In order to sense the stem diameter variation, a system composed of a displacement transducer and the necessary electronic circuits to drive the transducer and measure its displacement was designed. A block diagram of the system is given in Figure 10. The position transducer is composed of the LVDT and housing. The electronic circuits, in terms of function, are divided into oscillator, position-to-negative DC converter, amplifier driver and demodulators.

Displacement Transducer

The displacement transducer is made up of an LVDT and the housing, the latter providing the necessary mechanical support to keep the LVDT firmly attached to the plant.
Figure 10. Block diagram of the system. -- Notice how the sensor core is driven by the stem (Diaz-Munoz, 1980).
Linear Variable Differential Transformer (LVDT). The linear variable differential transformer (LVDT) (see Figure 10), is a very common mutual inductance element used to measure displacement. It produces an electrical output proportional to the displacement of a separate movable core. AC carrier excitation is applied to the primary. Two identical secondaries, symmetrically spaced from the primary, are connected externally in a series-opposing circuit. Motion of the non-contacting magnetic core varies the mutual inductance of each secondary to the primary which in turn determines the voltage induced from the primary to each secondary. If the core is centered between the secondary windings, the voltage induced in each secondary is identical and in series opposition so there is no net output. If the core is moved off the center, the mutual inductance of the primary with one secondary will be greater than with the other, and a differential voltage will appear across the secondaries in series. For core displacements within the operation range, the output voltage is essentially a linear function of displacement.

The LVDT's have several features that make them useful for position measurements (see Herceg, 1972). Among them, linearity, sensitivity, resolution and repeatability, low core friction and infinite mechanical life are the most important features for our purposes.

Linearity: The output voltage of an LVDT is a linear function of core displacement within a specified range of motion. Usually it is expressed as a percent of full range output. The linearity of our LVDT is ± 0.15 percent of full scale.
Sensitivity: Sensitivity is specified in terms of nominal full-scale output. The units are mv/μm/input volt. This is the LVDT output voltage with the core positioned at full-scale displacement divided by the primary excitation voltage. The Schaevitz model 025 MHR has a sensitivity of 0.33 mv/μm/input volt at 10 KHz.

Resolution and Repeatability: The smallest core displacement change which can be observed at the LVDT output is called resolution. Since infinitesimal changes in core position can be observed, the resolution is only limited by the electronics resolution.

In addition to the resolution, the LVDT's have the ability to reproduce the same output voltage for repeated trials at the same core position. This is called repeatability.

Core Frictionless: Ordinarily in a LVDT, there is no physical contact between the movable core and coil structure that permits core movements almost without friction. This permits LVDT use on critical measurements that can tolerate the addition of low-mass core but cannot tolerate friction loading.

Infinite Mechanical Life: The absence of friction and contact between the coil and core produce no wear of the LVDT parts, and the vacuum-impregnated moisture-resistant varnish to prevent corrosion, made the LVDT a very long-life device.

Temperature Effects: Not everything is so favorable in the LVDT's; they do have operating constraints. The most important effect is due to temperature. A rise in transformer temperature produces an
increase in the resistance of the copper wire ordinarily used to wind the primary and secondary coils. This produces a change in the output voltage level. Fortunately, there are two ways to avoid the resistance change with temperature. One is increasing the excitation frequency so that the inductive reactance becomes the predominant part of the impedance. Secondly, if one uses a high impedance load, the effect of the resistance change is not an important factor. Typical values of the internal resistance for the 025 MHR are 80 ohms for the primary and 40 ohms for each secondary. The reactance impedance at 10 KHz is 270 ohms at the input and 550 ohms of the two secondaries in series.

Excitation Frequency. An LVDT can be designed for operation at any frequency in the range from 50 Hz to the radio frequency region. However, standard transformers for industrial applications are supplied for operation in the 50 to 25,000 Hz range.

A higher LVDT excitation frequency can usually be employed with better results than that obtained at lower frequencies because sensitivity and efficiency generally increase with excitation frequency. Another factor is that at high frequency, the impedance of the primary and secondary coils increase, producing a decrease of the power consumption. In our case, a frequency of 10 KHz was selected.

Housing. For proper attachment of the LVDT to the plant, a special housing was designed (see Figure 11). The material used to build the housing was a special epoxy-impregnated fiberglass, G10. It has the special characteristics of not permitting moisture
Figure 11. LVDT and housing in-situ (Diaz-Munoz, 1980).
absorption, so that the dimensions of the housing remains constant regardless of moisture conditions in the canopy.

The housing has a rectangular shape, 3 x 2.5 cm, with four arms that hold the attaching screws. The arms are 2.5 cm long. To keep the unit as light as possible, unnecessary material was removed, resulting in a total housing weight of 11.7 grams. A 0.96 cm hole was drilled in the center part of the housing to permit the LVDT installation. An adjusting screw was added in one side to fix the LVDT in the proper position.

The attaching screws, placed in the housing arms, can be adjusted to hold plant stems up to 1.5 cm in diameter. The tip of each screw has a small, round front piece made of fiberglass that permits the adjusting of the screws without damage to the plant stem. Once the screws were fixed, they were left in the same position for the remainder of the season. The structure remained in place during the season regardless of the atmospheric conditions.

LVDT's Driver-Meter

In the electromechanical measuring system proposed for stem diameter measurements, the transducer was discussed in the previous sections. Now, let's focus our attention on the electronic circuitry needed to drive the LVDT's and to demodulate the LVDT output. To drive the LVDT's, an oscillator and an amplifier-drive was used. To demodulate the carrier signal from the LVDT, a precision AC-to-DC converter was used. In addition, for proper operation of the above circuits, a
DC-to-DC converter was designed to provide a negative voltage from the positive voltage of the battery.

**Oscillator.** To provide a sinusoidal signal of 10 KHz for driving the LVDT's, a precision waveform generator ICL 8038 was used. The ICL 8038 is a monolithic integrated circuit (IC), capable of producing sine, square, triangular and sawtooth waveforms of high accuracy (see Intersil Data Book, 1979). The frequency can be selected using minimum external components and is highly stable over a wide temperature and power supply range. Typical frequency drift with temperature is 50 ppm/°C and the typical drift with supply voltage change is 0.05%/volt.

The basic waveform generated internally in the ICL 8038 is a triangular wave. The symmetry of this wave can be adjusted with external timing resistors that control the time of rise and fall. When both rising and falling time are equal, a 50 percent duty cycle is achieved. The sine waveform is generated by piecewise approximation of the triangular waveform when it is working at 50 percent duty cycle. The square waveform is generated by the internal flip-flop that controls the electronic switch that changes the slope of the triangular wave. The output transistor for the square waveform has the open-collector configuration.

On Figure 12, one finds the oscillator configuration with its external components. R₁ and R₂ are the resistors that control the rising and falling times of the waveform. If R₁ = R₂, we can achieve a 50 percent duty cycle. The criteria to select R₁ and R₂ is given by the manufacturer as follows:
Figure 12. Oscillator and DC-to-DC converter.
where \( 10 \mu A < I < 1 \) ma. We choose \( R_1 = R_2 = 6,600 \Omega \pm 1 \) percent. With these values for \( R_1 \) and \( R_2 \), and \( V_{cc} = 12 \) v, the current \( I = 0.4 \) ma, which is in the acceptable range.

The capacitor \( C_1 \) is the one which is charged and discharged to produce the triangular waveform. Its value is evaluated according to the following equation:

\[
C_1 = \frac{0.3}{R_f}
\]

where \( R_1 = R_2 = R \) (ohms); \( f \) = operating frequency (Hz). For values of \( R = 6,600 \) and \( f = 10 \) KHz, the calculated value for \( C_1 \) is equal to 4,545 pf. This is not a standard value, so we chose \( C_1 = 4,700 \) pf, which is a good approximation.

Resistor \( R_3 \), according to the manufacturer, is used to minimize the sine-wave distortion. A recommended value for \( R_3 \) is 82 Kohms.

Due to the fast transition characteristics of the internal switches, undesired pulses may be transmitted to the power line. To eliminate those pulses, a capacitor \( C_3 = 10 \) \( \mu \)f was connected between the power line pin to ground. However, a very narrow pulse still was present, so another capacitor \( C_2 = 0.1 \) \( \mu \)f was added to eliminate these additional pulses.

DC-to-DC Converter. It was mentioned in the introduction chapter that the system was going to operate with batteries recharged with solar cells. Having only one positive voltage, a DC-to-DC converter
was designed to obtain a negative voltage for proper operation of the operational amplifiers used in the system.

Because the operational amplifiers have low power consumption and do not consume more than 10 mA altogether, a simple DC-to-DC converter was used. On the bottom part of Figure 12, one can see the circuit used to generate the negative voltage. It is controlled directly by the square waveform of the oscillator. To provide enough current to drive transistors $T_1$ and $T_2$, two CMOS non-inverting buffers are connected in parallel. Their input was connected to the square wave output of the oscillator and their output to resistors $R_5$ and $R_6$.

If the buffers' output is low, transistor $T_2$ is on cut-off and transistor $T_1$ is in saturation. The capacitor $C_5$ is charged across $T_1$ and $D_2$. When the square wave changes to a high level, then transistor $T_1$ is in cut-off and transistor $T_2$ is conducting. This forces the capacitor $C_5$ to discharge a negative voltage into capacitor $C_6$. The negative voltage is stored in $C_6$. Notice that $C_6$ is 250 $\mu$F whereas $C_5$ is only 4.5 $\mu$F. The reason for $C_5$ to be small is that it has to be charged in 1/2 of the square wave period, which in our case is 0.1 m-sec.

Resistor $R_4$ is used to connect the open collector transistor configuration of the ICL 8038 to the power supply for proper operation. Resistors $R_5$ and $R_6$ are used to limit the base current of the transistors.

**Amplifier-Driver.** The maximum nominal output voltage of the ICL 8038 is $0.2 \ V_{cc} = 0.2 \times 12 = 2.4$ RMS at 1 mA load current, and decrease to about $0.18 \ V_{cc}$ as the current increases by a factor of 10.
The output signal has a DC level equal to \( \frac{1}{2} V_{cc} \). If one considers that 12 LVDT's are going to be driven in parallel and that each LVDT needs 9 ma for 2.5 V input voltage, then it is obvious that an amplifier-driver is needed to set the proper voltage and current.

The amplifier-driver was built adding a power output stage to an operational amplifier CA 3140, as is shown on Figure 13. The output stage had to overcome several of the following constraints. It had to be operating only in the positive region because the negative voltage source could not provide enough energy for operating in the negative region. The output voltage swing had to be over 8.5 Vpp to provide 3 VRMS required for driving the LVDT primary. Finally, the output stage had to be capable of providing at least 110 ma to drive 12 LVDT's.

Configurations shown in Figure 13 overcome the above constraints. Both \( T_4 \) and \( T_6 \) are power transistors. \( T_3 \) and \( T_4 \) form a Darlington configuration with an equivalent \( \beta_T = \beta_3 \beta_4 \) such that the voltage drop across \( R_{11} \) due to \( I_{B3} = I_L/\beta_T \) is small, allowing the maximum positive output voltage. From the circuit, we see that \( V_0 = V_{cc} - R_{11} I_{B3} - V_{BE3} - V_{BE4} \), keeping \( I_{B3} \) small, and assuming \( V_{BE} = 0.6 \) V then the maximum positive value of \( V_0 = V_{cc} - 1.6 \) V. In this darlington configuration, \( V_0 \) follows the voltage \( V_1 \). From this circuit, one sees that:

\[
V_3 = V_0 + V_{BE3} + V_{BE4}
\]

\[
V_3 = V_1 + V_{D3} + V_{D4}
\]
Figure 13. Amplifier-driver scheme.
The capacitor $C_{12}$ was added to this configuration to avoid undesired oscillations of the system.

Transistors $T_5$ and $T_6$ form a PNP-NPN feedback pair combination. Transistor $T_5$ controls the output voltage by controlling the base current of $T_6$. If $T_5$ has a high value of $\beta$, then the voltage drop $V_5$ across $R_{12}$ will be small such that $V_0 \approx V_{BE5} \approx 0.6$ V. Now let's see if the $T_5 - T_6$ configuration follows the voltage $V_1$. From the circuit, we see that:

$$V_0 = V_5 + V_{BE5} \quad \text{and} \quad V_5 = V_1 - V_{D5}$$

If $V_{BE5} \approx V_{D5}$, then

$$V_0 \approx V_1$$

Resistors $R_9$, $R_{10}$ and capacitor $C_8$ were added to the operational amplifier-power output stage configuration to form an AC-coupled non-inverting amplifier. The gain of the circuit is given by the following equation:

$$G = \frac{(R_9 + R_{10})C_8}{R_9C_8s + 1} \quad (20)$$

for the values of $R_9$, $R_{10}$, $C_8$ at 10 KHz.
\[ G = 1 + \frac{R_{10}}{R_9}; \]  

\( R_{10} \) is variable for proper gain adjustments. The gain at DC is:

\[ G = 1 \]

The maximum symmetrical output voltage, \( V_0 \), is obtained when the DC level at the output is \( V_{cc}/2 \). This is achieved by means of the resistors \( R_7 \) and \( R_8 \) that provides a DC voltage level equal to \( V_{cc}/2 \) to the non-inverting input of the operational amplifier. A DC decoupling between the operational amplifier and the oscillator is achieved by capacitor \( C_7 \).

**AC-to-DC Converter.** Due to the relatively high frequency operation, 10 KHz of the LVDT's, its output signal could not be read by a conventional voltmeter, neither could it be converted to digital code by the dual slope A/D converter being used. To overcome this problem, a precision AC-to-DC converter was designed to demodulate the AC carrier signal. The circuit is in Figure 14.

To explain the operation of the AC-to-DC converter, we are going to analyze the behavior of the circuit first during the positive part of the sinusoidal cycle and then during the negative part. During the positive part, the output of the operational amplifier IC6, goes to a negative voltage forward polarizing diode \( D_9 \). The high open loop gain of the operational amplifier eliminates the non-linearities of the diode, so the gain \( G_1 = \frac{e_1}{e_i} = -\frac{R_{21}}{R_{19}} \). If \( R_{21} = R_{19} \), then \( e_1 = -e_i \).
Figure 14. Precision AC-to-DC converter.
The second operational amplifier IC7 is connected as a combination of a low pass filter and a summing amplifier. The output voltage of this circuit is given by:

\[ E_{\text{OUT}} = -\frac{R_{24}}{R_{24}C_{20}s + 1} \left( \frac{e_i}{R_{20}} + \frac{e_1}{R_{22}} \right) \]

If \( R_{20} = 2R_{22} \) and \( e_1 = -e_i \), then:

\[ E_{\text{OUT}} = \frac{R_{24}}{R_{24}C_{20}s + 1} \frac{1}{R_{20}} e_i \]  \hspace{1cm} (21)

One can see from this equation that the output voltage \( E_{\text{OUT}} \) is proportional to the positive part of the sinusoidal cycle.

Now let's analyze what happens to the output voltage during the negative part of the cycle. During this part, as soon as the input voltage \( e_i \) reaches a negative value, the output of the operational amplifier IC6 becomes positive forward polarizing the diode \( D_g \) and reverse-polarizing \( D_g \). The voltage at the inverting input remains at 0 volts due to the strong feedback of diode \( D_8 \). Because of the reverse polarization of diode \( D_g \), the voltage \( e_1 \) is equal to zero; then the output voltage \( E_{\text{OUT}} \) will be:

\[ E_{\text{OUT}} = -\frac{R_{24}}{R_{24}C_{20}s + 1} \left( \frac{e_i}{R_{20}} + \frac{0}{R_{22}} \right) \]

but \( e_i \) is now a negative voltage, then \( E_{\text{OUT}} \) becomes:

\[ E_{\text{OUT}} = \frac{R_{24}}{R_{24}C_{20}s + 1} \frac{1}{R_{20}} e_i \]  \hspace{1cm} (22)
From Equations 21 and 22, we see that for both the positive and negative parts of the waveform, the output $E_{\text{OUT}}$ is positive and equal. The low pass filter section gives an average of the full rectified waveform from the LVDT. Details of precision full wave rectifiers can be found in Tobey, Graeme and Huelsman, 1971, and Dobking, 1969a.

The operational amplifiers LM 108A were selected for the full wave precision rectifier. The main characteristics are:

- Operating temperature range: $-55^\circ\text{C}$ to $+125^\circ\text{C}$
- Low offset voltage: $< 0.5 \text{ mV}$
- Low offset voltage drift: $< 5 \mu \text{V/}^\circ\text{C}$
- Low power consumption: $< 25 \text{ mW}$
- Slew rate: $0.5 \text{ v/}\mu\text{sec}$

The LM 108A are not fast operational amplifiers; but adding the capacitor $C_{18}$ for feed-forward compensation, the slew rate is increased to about $10 \text{ v/}\mu\text{sec}$, extending the usefulness of the device to frequencies an order of magnitude (see Dobking, 1969b).

For our purpose, only one AC-to-DC converter should be needed to detect the changes in the output voltage of the LVDT. The equation that governs this process is:

$$d = (M_{p1} - M_{p2})V_i = AV_0$$

where

- $A$ = proportionality constant ($\frac{\mu\text{m}}{\text{volt}}$)
- $d$ = displacement of the LVDT ($\mu\text{m}$)
\[ M_{p1} = \text{mutual inductance between the primary and the secondary} \]
\[ 1(\text{Hy}) \]
\[ M_{p2} = \text{mutual inductance between the primary and the secondary} \]
\[ 2(\text{Hy}) \]
\[ V_i = \text{primary excitation voltage (volts)} \]

This transduction equation should be enough to detect the core displacement provided that \( V_i \) is constant. Unfortunately, the oscillator is sensitive to changes in the power supply voltage. According to the above equation, these changes give an error in the displacement measurement. To solve this problem, we used another AC-to-DC converter to detect changes in the primary voltage and later performed a division for connection

\[ d = \frac{V_0}{K V_i} \]

where

\[ K = \text{proportionality constant (\( \mu \text{m} \))} \]

The above equation is independent of the primary voltage changes.

The circuit on Figure 15 is the result of assembling all individual circuits mentioned previously, the oscillator, the amplifier-driver, the DC-to-DC converter, and the AC-to-DC converter.

**Placement of LVDT's**

In implementing the experiment to measure the stem diameter variation in cotton plants, a series of several questions were addressed.
Figure 15. LVDT-driver-meter circuit (Diaz-Munoz, 1980).
1. Where was the best place to attach the LVDT's, e.g., trunk or branches?

2. Was there any difference in the reading by placing the LVDT's at a different height, \( h \), from the ground?

3. Did different plants give similar readings?

4. Did plants at one side of the field give similar readings than the ones at the middle of the canopy?

5. Could we measure one plant and interpolate for the entire canopy?

To address the above questions, we decided to use several LVDT's at different parts in the plant, and at different places in the canopy.

The experimental design is summarized in Figures 16a and 16b. In Figure 16a, three different LVDT's were placed on the plant trunk and two different branches, respectively. The three LVDT's had different orientation. Not all plants had this configuration; some had only two LVDT's attached, but they were separated one from the other.

In Figure 16b, one can see how the LVDT's were distributed in the canopy. From the LVDT-meter-driver box, wires were run via conduit at different beds in the canopy, placed at 12 m, 16 m, and 20 m from the box. Different plants in the beds were chosen to see if there was similar behavior between the ones in the same bed and between those at different beds.
Figure 16. LVDT placement in the plant and spatial distribution in the field. — a. Placement of LVDT's at different places in the plant; b. LVDT's spatial distribution in the canopy.
CHAPTER 4.

SYSTEM CALIBRATION AND TEST

Before installation of the system in the field, tests and calibration were performed under controlled conditions in the laboratory. Later, at the time of installation on the plant, calibration of the sensor unit in situ was done for proper setting of the LVDT's in the linear range and in phase with the stem variations. That is, if the stem increases in diameter, the LVDT output voltage rises, and vice versa.

Calibration

AC-to-DC Converter Gain Calibration

Although the manufacturers of the LVDT's (model 025 MHR) recommends a nominal input voltage of 3 V rms, it was decided to use 2.5 V rms to save energy. For this input voltage value, the gain of the AC-to-DC converter connected to the primary was adjusted to give a DC output voltage of one volt. The linearity of this circuit was checked against a digital voltmeter, Fluke model 8000A (3-1/2 digits).

A similar gain calibration was performed to the AC-to-DC converter connected to the LVDT's secondary winding. The only difference was that before any adjustment of the gain, the LVDT was mounted on a special mechanical displacement calibrator that accommodates the LVDT body on one side and has a rotating spindle micrometer head on the other
side that pushes the LVDT core back and forth. The displacement range of the micrometer head is one inch. Once the LVDT was set into the calibrator, the micrometer head was adjusted to give zero volts at the LVDT output, then the core was displaced 635 μm from the center. At this point, the gain of the secondary AC-to-DC converter was adjusted to give one volt DC at the output with 2.5 V rms at the input.

LVDT Displacement Calibration

Using the mechanical calibrator just described above, a test of several LVDT's output voltage versus displacement was performed. The output voltage of the secondary was read at the secondary AC-to-DC converter output. The average of the data after five trials was obtained. Typical data for one LVDT is shown in Table 1.

From the data of Table 1, Figure 17 was obtained. It represents the average deviation of the LVDT output readings from the true value, which was evaluated as TRUE VALUE = 1.575 \( \frac{mv}{\mu m} \) displacement (μm), where \( m = 1,000 \text{ mv/635}\mu m = 1.575 \text{ mv/}\mu m \). The non-linearity is ± 0.22 percent of full scale, which is very good.

System Power Supply Sensitivity

It was mentioned before that the amplitude of the oscillator output voltage may change with the power supply voltage. To avoid that problem, the transduction equation was developed:

\[ d = K \frac{V_0}{V_{in}}; \quad K = 635 \mu m \]
Figure 17. Linearity of the transducer. -- 1 mil = 25.4 microns (Diaz-Munoz, 1980).
Table 1. LVDT displacement calibration

<table>
<thead>
<tr>
<th>Core Position</th>
<th>Output Voltage (mV)</th>
<th>True Value (mV)</th>
<th>Deviation (mV)</th>
<th>Deviation % of Full Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 μm</td>
<td>1.2</td>
<td>0</td>
<td>1.2</td>
<td>12%</td>
</tr>
<tr>
<td>50.8 mils</td>
<td>82.2</td>
<td>80</td>
<td>2.2</td>
<td>22%</td>
</tr>
<tr>
<td>101.6 mils</td>
<td>162.2</td>
<td>160</td>
<td>2.2</td>
<td>22%</td>
</tr>
<tr>
<td>152.4 mils</td>
<td>242.1</td>
<td>240</td>
<td>2.1</td>
<td>21%</td>
</tr>
<tr>
<td>203.2 mils</td>
<td>322.1</td>
<td>320</td>
<td>2.1</td>
<td>21%</td>
</tr>
<tr>
<td>254.0 mils</td>
<td>402.0</td>
<td>400</td>
<td>2.1</td>
<td>21%</td>
</tr>
<tr>
<td>304.8 mils</td>
<td>482.0</td>
<td>480</td>
<td>2.0</td>
<td>20%</td>
</tr>
<tr>
<td>355.6 mils</td>
<td>561.4</td>
<td>560</td>
<td>1.4</td>
<td>14%</td>
</tr>
<tr>
<td>406.4 mils</td>
<td>640.2</td>
<td>640</td>
<td>0.2</td>
<td>02%</td>
</tr>
<tr>
<td>457.2 mils</td>
<td>720.0</td>
<td>720</td>
<td>0.0</td>
<td>00%</td>
</tr>
<tr>
<td>508.0 mils</td>
<td>800.0</td>
<td>800</td>
<td>0.0</td>
<td>00%</td>
</tr>
<tr>
<td>558.8 mils</td>
<td>880.0</td>
<td>880</td>
<td>0.0</td>
<td>00%</td>
</tr>
<tr>
<td>609.6 mils</td>
<td>960.0</td>
<td>960</td>
<td>0.0</td>
<td>00%</td>
</tr>
</tbody>
</table>
Because $V_o$ is a function of $V_{in}$, any change in the input voltage, $V_{in}$, the output voltage $V_o$ will also change, leaving the value $d$ constant. To verify that, we performed an experiment where the displacement $d$ was set at a fixed value of 311.15 μm from the center position. The power supply voltage was changed such that the primary output voltage varied from 0.9 V to 1.1 V DC (maximum range expected). The $d$ values were calculated for each reading. It was found that there was a maximum deviation of 1.13 percent from the true value (311.15 μm). The data obtained is in Table 2.

Table 2. Sensitivity to power supply variations

<table>
<thead>
<tr>
<th>Primary Voltage Volts</th>
<th>Secondary Voltage Volts</th>
<th>$d$ μm</th>
<th>Deviation % of True Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.100</td>
<td>0.548</td>
<td>314.90</td>
<td>1.07</td>
</tr>
<tr>
<td>1.054</td>
<td>0.520</td>
<td>313.28</td>
<td>0.68</td>
</tr>
<tr>
<td>1.016</td>
<td>0.499</td>
<td>311.87</td>
<td>0.23</td>
</tr>
<tr>
<td>1.000</td>
<td>0.490</td>
<td>311.15</td>
<td>0.00</td>
</tr>
<tr>
<td>0.975</td>
<td>0.477</td>
<td>310.66</td>
<td>-0.16</td>
</tr>
<tr>
<td>0.950</td>
<td>0.463</td>
<td>309.47</td>
<td>-0.54</td>
</tr>
<tr>
<td>0.925</td>
<td>0.449</td>
<td>308.23</td>
<td>-0.94</td>
</tr>
<tr>
<td>0.900</td>
<td>0.436</td>
<td>307.62</td>
<td>-1.13</td>
</tr>
</tbody>
</table>

The conclusion of this test is that the transduction equation works with an error of about one order of magnitude less than the output voltage change introduced by the power supply variation.
Temperature Testing

AC-to-DC Converter Temperature Test

Both the primary and secondary AC-to-DC converters were tested against temperature. To perform the test, the inputs of both converters were grounded. The output voltage at different temperatures were recorded. The data is shown in Table 3.

Table 3. AC-to-DC converter temperature test

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Primary Output Volts</th>
<th>Secondary Output Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>40</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>50</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>60</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>70</td>
<td>0.001</td>
<td>0.004</td>
</tr>
<tr>
<td>80</td>
<td>0.001</td>
<td>0.004</td>
</tr>
</tbody>
</table>

One sees that both converters are practically insensitive to temperature. The secondary shows an output voltage drift of 25 μV/°C.

LVDT-Housing Assembly Temperature Test

Due to the extreme temperature conditions in the canopy, dimension changes by distortion of the LVDT housing were expected. Error compensation of housing distortion was minimized by placing a small screw made of the same material as the housing between the LVDT core and the plant stem. Figure 18 illustrates this small screw (the core
Figure 18. Cross-section of the sensor assembly showing the adjusters position, the core position, and coils.
adjuster). The compensation principle is as follows. If the LVDT body is adjusted a distance \( a \) from the stem center, as one sees in Figure 18, and the LVDT core is adjusted a distance \( b \) from the stem surface, then if \( a \) and \( b \) are similar, for any change of the distance \( a \) due to distortion of the housing arm, \( b \) will change in the same direction, providing the compensation desired.

To see how effectively the LVDT-housing temperature compensation system operated, the assembly was mounted as in Figure 11, replacing the plant stem by a pyrex glass tube with low temperature coefficient, and the LVDT position was fixed at 312.5 \( \mu \text{m} \) from the center point. The assembly was placed into an oven, and the temperature was varied from 30\( ^\circ \text{C} \) to 80\( ^\circ \text{C} \). The data obtained is on Table 4.

Table 4. Sensing unit temperature test

<table>
<thead>
<tr>
<th>Temperature ( ^\circ \text{C} )</th>
<th>Secondary Output Volts</th>
<th>( d ) Displacement ( \mu \text{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.500</td>
<td>312.5</td>
</tr>
<tr>
<td>35</td>
<td>0.500</td>
<td>312.5</td>
</tr>
<tr>
<td>40</td>
<td>0.502</td>
<td>318.8</td>
</tr>
<tr>
<td>45</td>
<td>0.5025</td>
<td>319.1</td>
</tr>
<tr>
<td>50</td>
<td>0.502</td>
<td>318.8</td>
</tr>
<tr>
<td>55</td>
<td>0.5035</td>
<td>319.7</td>
</tr>
<tr>
<td>60</td>
<td>0.503</td>
<td>319.4</td>
</tr>
<tr>
<td>65</td>
<td>0.5025</td>
<td>319.1</td>
</tr>
<tr>
<td>70</td>
<td>0.503</td>
<td>319.4</td>
</tr>
<tr>
<td>75</td>
<td>0.5035</td>
<td>319.7</td>
</tr>
<tr>
<td>80</td>
<td>0.5045</td>
<td>320.3</td>
</tr>
</tbody>
</table>
The data of Table 4 is displayed in Figure 19. Using the least squares method to find the displacement versus temperature equation, an approximate slope of 0.1 μm/°C was determined. This indicates that the temperature influence on the sensor assembly is properly compensated.

LVDT's Field Calibration

Once the gain and temperature tests were performed in the laboratory, the system was moved to the field for testing the cotton plant stem diameter variation. At the time of attachment of the sensor unit to the plant, the LVDT's had to be calibrated for proper operation in the linear range. To be in phase with the stem growth, the operation region of the core was from the center to the rear part of the body. For the calibration procedure, refer to Figure 18. It is as follows:

1. Attach the LVDT housing firmly to the center of the stem by tightening the four screws placed one on each housing arm.
2. Loosen the coarse adjustor and insert the LVDT, pushing gently from the back until the output voltage is zero. Move a little bit farther such that the output voltage starts increasing. Stop at about 200 mv, then tighten the coarse adjustor to fix the LVDT body to the housing.
3. For fine adjustment, the little brass bar in the back of the LVDT is rotated. This bar is fixed to the core. If the LVDT is operating in the proper range, by turning the brass bar clockwise the output has to decrease. The LVDT output voltage increases by turning the bar counterclockwise.
Figure 19. Sensor assembly temperature variation (Diaz-Munoz, 1980).
4. For the initial setting of the LVDT, the minimum voltage depends on the time of day the calibration is made. The most convenient time for calibration is about 1500 hours, when the stem shrinkage is about maximum. We can then set the output voltage at about 150 mv and be sure that this is the minimum output voltage we may expect.

If performed properly, recalibration of the LVDT's initial value will have to be done about every five days because the normal plant stem expansion eventually will bring the LVDT out of range.

During the preliminary experiments, an undesired change in phase of the output voltage was detected in two LVDT's; that is, the LVDT core was working in the wrong linear range and as the stem diameter decreases, the LVDT output increased. Two things can cause this change in phase. First, the LVDT housing was not properly attached and subsequently shifted from the original position. Second, due to the constant pressure of the core adjustor tip against the stem, some of the soft tissue of the dermis compressed. Both of these theories were checked. However, evidence of possible housing shift was found. This implies that the problem will be eliminated with proper housing attachment.
CHAPTER 5

FIELD USE

Operation of the system in the field required constant supervision to assure the data obtained was valid. Operational manual recording of the data was employed because an automatic system was not ready. The following paragraphs will describe the procedure to manually operate the system.

Data Acquisition Procedure

The LVDT-driver-meter was placed on one side of the field. Wires for both the primary and secondary LVDT windings were run via a conduit to the plants. All LVDT primaries were connected in parallel to the LVDT driver. The LVDT secondaries had individual wires connected to a rotary switch for multiplexing. The switch common was connected to the input of the secondary AC-to-DC converter. All the LVDT secondary commons were attached to a single common wire which, in turn, was connected to the common of the LVDT-driver-meter. The LVDT's were calibrated according to the procedure outlined in Chapter 4 to assure its proper operating range. The data was obtained with a 3-1/2 digit voltmeter. The following procedure was repeated each 11 minutes, according to the following four steps.

1. The sampling time was recorded.
2. The primary voltage was recorded.
3. The rotary switch was set to measure LVDT #1. About 15 seconds were allowed for the secondary AC-to-DC converter to reach the steady state, then the output voltage reading was read with a 3-1/2 digit voltmeter.

4. The procedure was then repeated for the next 11 LVDT's.

The stem diameter measuring experiment process lasted more than one week, taking data daily, starting at 0500 in the morning and ending after midnight. Approximately 10,647 readings were taken. The data was collected between July 30 to August 8 of 1979. An irrigation schedule was covered and one LVDT's recalibration was performed.

Typical Data

Data obtained in the field was punched on computer cards for analysis in the computer. A typical data plot is shown on Figure 20a and 20b. In part 20a, the data displayed was obtained from the trunk measurements. The data in Figure 20b was obtained by measuring the diameter variations of one branch of the same plant. Notice that Figures 20a and 20b represent only the AC component of the data. The DC component associated with the plant growth was eliminated during the computer processing.

Problems Encountered

During the stem diameter measuring process, two problems were difficult to solve: a high frequency (1 MHz) voltage induced in the wires by a nearby radio station, and the change in phase of the LVDT's.
Figure 20. Typical data obtained during the stem diameter measurement experiment. -- (a) Shrinkage in the trunk; (b) shrinkage in a branch of the same plant.
The induced voltage problem was solved by using a second-order LC filter at the input of the secondary AC-to-DC converter.

The second problem is still not completely solved. The best attempt mode was tightening the attaching screws of the LVDT housing to prevent the change in phase of the LVDT output; but even with that, the change in phase still occurs.

**LVDT Recalibration**

The plant stem, besides its daily shrinkage due to diurnal water loss, steadily increases its diameter. Eventually this increase takes the LVDT out of its operation range. During the experiment, we found that a recalibration of the LVDT's in the linear range had to be done approximately every five days. The recalibrating procedure was outlined in Chapter 4.
CHAPTER 6

RESULTS

The analysis of the data collected during the 10 days the experiment was performed has yielded very interesting results. The most relevant of these will be outlined below.

Stem Diameter Variation Before, During, and After Irrigation

Deeper shrinkage in the stem diameter was anticipated during the time the plant was under water stress than the shrinkage when the plant was under no water deficit. To illustrate the validity of this hypothesis, the basic pattern of stem diameter variation is shown in Figure 21. The curves shown are for the day before irrigation (2 August, 1979), the day of irrigation (3 August 1979) and the day after irrigation (4 August 1979).

When the radiation loading begins to rise (about 700 hours), the plant begins to transpire water through the stomates in the leaves. As one can see on Figure 21, on August 2, the day before irrigation, there was a scarcity of water in the roots such that the plant could not meet its water necessities. The stem then performed a pronounced shrinkage. During the day of irrigation, the stem began with the same shrinkage pattern as the previous day; but at 1000 the field was irrigated and as soon as the water penetrated to the roots, the shrinkage
Figure 21. Basic pattern of stem diameter variation before, during and after irrigation (Diaz-Munoz, 1980).
of the stem diameter was abated and a slow recovery began. On 4 August (the day after irrigation) the plant was in a very low water stress condition and exhibited no shrinkage at all during the day.

In an experiment performed a year later, the same diameter shrinkage pattern was obtained (see Figure 22). This figure shows the stem diameter behavior during six consecutive days, one before irrigation and five after it. One can see how the stem shrinkage is bigger each day as the soil dries out.

**Stem Shrinkage at the Trunk and Branches.**

From the data obtained by measuring the stem shrinkage at different parts of the plant, it was observed that the amplitude of the shrinkage was bigger in the trunk than in the branches (see Figure 20). This was expected because there exists more phloem tissue in the trunk than in the branches.

**Phase Relations Between the Trunk and Branches**

Figure 20 represents the typical shrinkage in the trunk and branches. We can see there that although a different amplitude is present, the signals are in phase. In general, from the data obtained at different plants, trunk and branch shrinkage is in phase.

**Similar Readings at Different Plants**

During the experiment, five different plants, sufficiently distant from one another (see Figure 16), were chosen to see if there existed differences in the readings due to distance. From the data obtained, the plants behave similarly, independent of location.
Figure 22. Stem diameter variation sequence before and after irrigation.
Extrapolation of Results

The maximum separation between plants was about 10 meters. This is, however, a short distance in terms of soil and environmental variation. Therefore, extrapolation is difficult.
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

From the analysis of the results obtained during the time the experiment was performed, the following conclusions are possible:

1. Observing the difference in stem diameter shrinkage at different water stress conditions, as in Figure 21, one can see the feasibility of this method for water potential status determination and prediction of irrigation schedules.

2. The best readings for the stem shrinkage were obtained from the trunk. They had the largest amplitude and represented the integration of the individual water potentials generated in the leaves.

3. From the stem variation measurements on the trunk and branches, we observed that no appreciable phase shift occurs between them. This corroborates the theory that the vertical water potential gradient in the xylem is small, such that the water potential gradient between the phloem and xylem is about the same in the trunk and branches, producing a radial water flow.

4. Although the results obtained for different plants at different distances were similar, the distance between them (10 meters maximum) was not sufficient to extrapolate results. Our
conclusion here is that the plants behave in similar ways when they are close, but may or may not behave similarly when they are far apart.

**Recommendations**

From the experience obtained during the measurement period, the following recommendations are suggested:

1. Continuation of the research in the physical mechanism that forces water transport. Clarify some previous results, e.g., the validity of the time lag, $T_p$. Determine a reliable non-destructive method to quantify the water potential at any time by sensing the stem diameter.

2. Design of an automatic, continuous data acquisition system for stem shrinkage measurements.

3. Design of a connected via wireless telemetry independent monitoring station to bring the signals from any place in the canopy without the cumbersome installation of cables.

It is the opinion of the author that from the conclusions obtained that the goals of this thesis were successfully accomplished; and directions were established for future research.
APPENDIX

DEVICE SPECIFICATIONS
### LM108A/LM208A

**absolute maximum ratings**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>±20V</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Power Dissipation (Note 1)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Differential Input Current (Note 2)</td>
<td>±10 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Voltage (Note 3)</td>
<td>±15V</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Output Short-Circuit Duration</td>
<td>Indefinite</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Operating Temperature Range</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>LM108A</td>
<td>-55°C to 125°C</td>
<td></td>
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</tr>
<tr>
<td>LM208A</td>
<td>-25°C to 85°C</td>
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<td></td>
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<tr>
<td>Storage Temperature Range</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM208A</td>
<td>-65°C to 150°C</td>
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<td></td>
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</table>

**Lead Temperature (Soldering, 10 sec)**

- 300°C

**electrical characteristics (Note 4)**

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<th>PARAMETER</th>
<th>CONDITIONS</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNITS</th>
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<td>Input Offset Voltage</td>
<td>( T_A = 25^\circ \text{C} )</td>
<td>0.3</td>
<td>0.5</td>
<td></td>
<td>mV</td>
</tr>
<tr>
<td>Input Offset Current</td>
<td>( T_A = 25^\circ \text{C} )</td>
<td>0.05</td>
<td>0.2</td>
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<td>nA</td>
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<td>Input Bias Current</td>
<td>( T_A = 25^\circ \text{C} )</td>
<td>0.8</td>
<td>2.0</td>
<td></td>
<td>nA</td>
</tr>
<tr>
<td>Input Resistance</td>
<td>( T_A = 25^\circ \text{C} )</td>
<td>30</td>
<td>70</td>
<td></td>
<td>( \text{M\Omega} )</td>
</tr>
<tr>
<td>Supply Current</td>
<td>( T_A = 25^\circ \text{C} )</td>
<td>0.3</td>
<td>0.6</td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>Large Signal Voltage Gain</td>
<td>( T_A = 25^\circ \text{C}, \ V_S = \pm 15V ) ( V_{\text{OUT}} = \pm 10V, R_L &gt; 10 \text{k}\Omega )</td>
<td>80</td>
<td>300</td>
<td></td>
<td>V/mV</td>
</tr>
<tr>
<td>Input Offset Voltage</td>
<td>( V_{\text{OUT}} = \pm 10V, R_L &gt; 10 \text{k}\Omega )</td>
<td>1.0</td>
<td>5.0</td>
<td></td>
<td>( \mu \text{V/}^\circ \text{C} )</td>
</tr>
<tr>
<td>Average Temperature Coefficient of Input Offset Voltage</td>
<td>( T_A = 25^\circ \text{C} )</td>
<td>0.4</td>
<td></td>
<td></td>
<td>nA</td>
</tr>
<tr>
<td>Average Temperature Coefficient of Input Offset Current</td>
<td>( T_A = 25^\circ \text{C} )</td>
<td>0.5</td>
<td>2.5</td>
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<td>pA/°C</td>
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<tr>
<td>Input Bias Current</td>
<td>( T_A = -125^\circ \text{C} )</td>
<td>3.0</td>
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<td>nA</td>
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<tr>
<td>Supply Current</td>
<td>( V_S = \pm 15V ) ( R_L &gt; 10 \text{k}\Omega )</td>
<td>0.15</td>
<td>0.4</td>
<td></td>
<td>mA</td>
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<tr>
<td>Large Signal Voltage Gain</td>
<td>( V_S = \pm 15V ) ( V_{\text{OUT}} = \pm 10V )</td>
<td>40</td>
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<td>V/mV</td>
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<tr>
<td>Output Voltage Swing</td>
<td>( V_S = \pm 15V ) ( R_L = 10 \text{k}\Omega )</td>
<td>±13</td>
<td>±14</td>
<td></td>
<td>V</td>
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<tr>
<td>Input Voltage Range</td>
<td>( V_S = \pm 15V )</td>
<td>96</td>
<td>110</td>
<td></td>
<td>dB</td>
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<tr>
<td>Common Mode Rejection Ratio</td>
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<td>96</td>
<td>110</td>
<td></td>
<td>dB</td>
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<tr>
<td>Supply Voltage Rejection Ratio</td>
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</table>

**Notes**

1. The maximum junction temperature of the LM108A is 150°C, while that of the LM208A is 100°C. For operating at elevated temperatures, devices in the TO-5 package must be derated based on a thermal resistance of 150°C/W, junction to ambient, or 45°C/W, junction to case. For the flat package, the derating is based on a thermal resistance of 185°C/W when mounted on a 1/16-inch-thick epoxy glass board with ten 0.03-inch-wide, 2-ounce copper conductors. The thermal resistance of the dual-in-line package is 100°C/W, junction to ambient.

2. The inputs are shunted with back-to-back diodes for overvoltage protection. Therefore, excessive current will flow if a differential input voltage in excess of 1V is applied between the inputs unless some limiting resistance is used.

3. For supply voltages less than ±15V, the absolute maximum input voltage is equal to the supply voltage.

4. These specifications apply for 25V \( \leq V_S \leq 20V \) and -55°C \( \leq T_A \leq 125^\circ \text{C} \), unless otherwise specified. With the LM208A, however, all temperature specifications are limited to -25°C \( \leq T_A \leq 85^\circ \text{C} \).
MAXIMUM RATINGS

Supply Voltage ................................... ±18V or 36V Total
Power Dissipation ............................................. 750mW (Note 5)
Input Voltage (any pin) Not To Exceed Supply Voltages
Input Current (Pins 4 and 5) 25mA
Output Sink Current (Pins 3 and 9) 25mA
Storage Temperature Range: -65°C to +125°C
Operating Temperature Range: 8038AM, 8038BM -55°C to +125°C
8038AC, 8038BC, 8038CC 0°C to +70°C
Lead Temperature (Soldering, 10 sec.) ... 300°C

ELECTRICAL CHARACTERISTICS

(Vs = ±10V or ±20V, TA = 25°C, Rl = 10 kΩ, Unless Otherwise Specified) Note 3.

<table>
<thead>
<tr>
<th>GENERAL CHARACTERISTICS</th>
<th>MIN</th>
<th>8038CC TYP</th>
<th>MAX</th>
<th>8038BC/BM TYP</th>
<th>MAX</th>
<th>8038AC/AM TYP</th>
<th>MAX</th>
<th>UNITS</th>
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<tr>
<td>Supply Voltage Operating Range</td>
<td>±10</td>
<td>+20</td>
<td>±10</td>
<td>+20</td>
<td>±10</td>
<td>+20</td>
<td>V</td>
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<tr>
<td>Supply Current (Vs = ±10V) Note 1,</td>
<td>+15</td>
<td>+15</td>
<td>+15</td>
<td>+15</td>
<td>+15</td>
<td>+15</td>
<td>mA</td>
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<tr>
<td>8038AM, 8038BM</td>
<td>12</td>
<td>15</td>
<td>12</td>
<td>15</td>
<td>12</td>
<td>15</td>
<td>mA</td>
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<tr>
<td>8038AC, 8038BC, 8038CC</td>
<td>12</td>
<td>20</td>
<td>12</td>
<td>20</td>
<td>12</td>
<td>20</td>
<td>mA</td>
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<tr>
<td>FREQUENCY CHARACTERISTICS (all waveforms)</td>
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<tr>
<td>Maximum Frequency of Oscillation</td>
<td>100,000</td>
<td>100,000</td>
<td>100,000</td>
<td>100,000</td>
<td>Hz</td>
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<tr>
<td>Sweep Frequency of Freq.</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>kHz</td>
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<td>40</td>
<td>kHz</td>
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<td>FM Linearity</td>
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<td>0.2</td>
<td>0.2</td>
<td>%</td>
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<td>Frequency Drift With Temperature Note 6</td>
<td>50</td>
<td>100</td>
<td>20</td>
<td>50</td>
<td>ppm/bar</td>
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<td>Frequency Drift With Supply Voltage (Over Supply Voltage Range)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>%/V</td>
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<tr>
<td>Recommended Programming Revisions (Rf and Rg)</td>
<td>1000</td>
<td>14</td>
<td>1000</td>
<td>14</td>
<td>1000</td>
<td>14</td>
<td>Ω</td>
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<td>OUTPUT CHARACTERISTICS</td>
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<tr>
<td>Square-Wave</td>
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<tr>
<td>Leakage Current (Vs = 30V)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>µA</td>
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<tr>
<td>Saturation Voltage (IRs = 2mA)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>V</td>
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<td>Rise Time (Rs = 4.7kΩ)</td>
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<td>100</td>
<td>100</td>
<td>ms</td>
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<td>Fall Time (Rs = 4.7kΩ)</td>
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<td>40</td>
<td>40</td>
<td>ms</td>
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<td>Duty Cycle Adjust</td>
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<td>98</td>
<td>2</td>
<td>98</td>
<td>%</td>
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<tr>
<td>Triangle/Sine/Ramp/Ramp</td>
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<tr>
<td>Amplitude (IR = 100kΩ)</td>
<td>0.30</td>
<td>0.33</td>
<td>0.30</td>
<td>0.33</td>
<td>xVs</td>
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<tr>
<td>Linearity</td>
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<td>0.05</td>
<td>0.05</td>
<td>%</td>
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<tr>
<td>Output Impedance (ZOUT = 5mA)</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>Ω</td>
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<td>Sine-Wave</td>
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<tr>
<td>Amplitude (IR = 100kΩ)</td>
<td>0.2</td>
<td>0.22</td>
<td>0.2</td>
<td>0.22</td>
<td>xVs</td>
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<tr>
<td>THD (IR = 100kΩ)</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
<td>1.5</td>
<td>%</td>
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<td>THD Adjusted (Use Fig. 8b)</td>
<td>0.5</td>
<td>0.5</td>
<td>%</td>
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</tr>
</tbody>
</table>

NOTE 1: Rf and Rg collection currents not included.
NOTE 2: Vs = 20V; Rs and Rs = 10kΩ, f = 9kHz; Can be extended to 1000. See Figures 13 and 14
NOTE 3: All parameters measured in test circuit given in Fig. 2
NOTE 4: 82kΩ connected between pins 11 and 12, Triangle Duty Cycle set at 50%. (Use Rf and Rg).
NOTE 5: Derate plastic package at 6.7mW/°C for ambient temperatures above 50°C
NOTE 6: Derate ceramic package at 12.5mW/°C for ambient temperatures above 100°C
NOTE 7: Over operating temperature range, Fig. 2, pins 7 and 8 connected, Vs ±10V. See Fig. 6c for T.C. vs Vs.
SCHAEVITZ
MINIATURE — MHR SERIES

For Differential Output Tie
Secondary Leads Blu & Grn Together.

### GENERAL SPECIFICATIONS
- **Input Voltage**: 3 V rms (nominal)
- **Frequency Range**: 400 Hz to 20 KHz
- **Temperature Range**: -65°F to +300°F
- **Null Voltage**: Less than 0.5% full scale output
- **Shock Survival**: 1000 g for 11 milliseconds
- **Vibration Tolerance**: 20 g up to 2 KHz
- **Coil Form Material**: Series 400 magnetic stainless steel
- **Housing Material**: Laminated glass-epoxy
- **Lead Wires**: AWG 28, stranded copper, Teflon-insulated, 12 inches long

### TYPE | LINEAR RANGE (INCHES) | IMPEDANCE (OHMS) | SENSITIVITY (MV/0.001°V) | CARRIER PHASE SHIFT (DEG.) | LINEARITY (PERCENT) FULL RANGE | WEIGHT (GRAMS) | LENGTH (INCHES) BODY CORE BODY CORE
<table>
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<tr>
<th></th>
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<th></th>
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<tbody>
<tr>
<td>005 MHR</td>
<td>0.005</td>
<td>60 75 26 315</td>
<td>2.7 8.4</td>
<td>-71 48</td>
<td>0.20 0.26 0.30 0.40</td>
<td>2 0.1</td>
<td>0.38 0.18 0.18</td>
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<td>010 MHR</td>
<td>0.010</td>
<td>80 150 200 420</td>
<td>3.2 6.1</td>
<td>-58 14</td>
<td>0.10 0.25 0.35 0.35</td>
<td>3 0.2</td>
<td>0.54 0.23 0.23</td>
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<tr>
<td>025 MHR</td>
<td>0.025</td>
<td>115 270 280 500</td>
<td>4.8 8.5</td>
<td>-71 32</td>
<td>0.15 0.26 0.25 0.30</td>
<td>6 0.4</td>
<td>0.66 0.40 0.40</td>
</tr>
<tr>
<td>050 MHR</td>
<td>0.050</td>
<td>140 450 50 150</td>
<td>2.7 3.3</td>
<td>-34 8</td>
<td>0.15 0.25 0.35 0.50</td>
<td>5 0.4</td>
<td>0.80 0.50 0.50</td>
</tr>
<tr>
<td>100 MHR</td>
<td>0.100</td>
<td>150 450 110 210</td>
<td>2.4 2.9</td>
<td>-30 5</td>
<td>0.15 0.25 0.25 0.30</td>
<td>6 0.5</td>
<td>1.00 0.62 0.62</td>
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<tr>
<td>250 MHR</td>
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<td>160 500 260 500</td>
<td>1.3 2.1</td>
<td>-28 4</td>
<td>0.15 0.25 0.35 0.50</td>
<td>9 0.9</td>
<td>1.85 1.12 1.12</td>
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<td>500 MHR</td>
<td>0.500</td>
<td>185 455 525 1200</td>
<td>1.8 2.4</td>
<td>-17 1</td>
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<td>17 1.6</td>
<td>3.30 2.00 2.00</td>
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<tr>
<td>1000 MHR</td>
<td>1.000</td>
<td>145 330 385 600</td>
<td>0.8 1.7</td>
<td>-5 -</td>
<td>0.20 0.25 0.50</td>
<td>26 2.5</td>
<td>5.60 3.00 3.00</td>
</tr>
</tbody>
</table>

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LIST OF REFERENCES


