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An improved strain-gauge device for continuous field measurement of stem and fruit diameter

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Abstract

An improved strain-gauge dendrometer was tested on apple (*Pyrus malus* L.) tree trunks and fruit to measure thickness dynamics. The sensor is similar to previous devices, but is more flexible allowing for a greater range of thickness change before it has to be physically reset. The practical resolution of the measurement system is given as one standard deviation about the mean of 51 observations taken on an Invar metal alloy in the field when temperatures ranged between 16 °C and 17 °C. The mean of these observations was 3.68356 mm with one standard deviation of 0.00947 mm. There is a positive correlation between temperature and sensor output having a slope of 2.96 μm °C^{-1}. For a typical daily temperature change of 21 °C, this causes an apparent change of 62 μm. Stem thickness varied 0.7 mm diurnally with maximum values at night and minimum values during the day. Apple fruit diameter increased 3.3 mm over the 15 d period.

Key words: Strain gauge dendrometer, plant stem and fruit thickness sensor, plant water status, growth.

Introduction

There is a need to measure dynamics of stem and fruit diameter to understand how plants respond to diurnal variation in water content and long-term growth conditions. Many studies have found relationships between stem diameter dynamics and temperature, light, humidity, rainfall, water, and air pollutants (Klepper *et al.*, 1971; Sheriff, 1976; Beedlow *et al.*, 1986; Garnier and Berger, 1986; Katerji *et al.*, 1994; Link *et al.*, 1995; Thiede *et al.*, 1995). Stems shrink during the day because plants lose more water by transpiration than they can take up. At night, when there is little loss of water, stems will increase in diameter because of the uptake and storage of water (Hinckley and Bruckerhoff, 1975). Less work has been done on fruit diameter dynamics (Tromp, 1984; Berger and Selles, 1993). Fruits may also shrink during the day by loss of water (Berger and Selles, 1993).

The measurement of change in stem diameter can be done with a caliper. Unfortunately, this technique is discontinuous and insensitive (Schütte and Burger, 1981). Linear variable differential transformers (LVDTs) have been used to measure stem diameters continuously (Klepper *et al.*, 1971; Berger and Selles, 1993). LVDTs, while better than a caliper, have to be mounted on a relatively large frame and can only measure one side of the stem (Bartholic, 1980; Schütte and Burger, 1981). More recent designs use strain gauges to detect changes in stem size through deformations in an attached metal housing (Beedlow *et al.*, 1986). The sensor described in Beedlow *et al.* (1986) is light, can remain attached to stems for months to years, and can detect micron-size changes. This sensor can measure diameter changes for long periods of time as long as stem diameter growth is slow as in desert shrubs (Link *et al.*, 1995). The sensor, in a stiff metal housing, has to be reset to a new zero point if the diameter increases by more than 1 mm to avoid deforming the stem or breaking the device.

This study describes a modification of the dendrometer (Beedlow *et al.*, 1986) that is more flexible, thus allowing measurements for diameter changes of up to 8 mm. This

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greater flexibility allows for the measurement of stem or fruit diameters on rapidly growing plants without resetting the sensor as often or deforming the tissue.

The objective of this study was to determine the operating characteristics of the new dendrometer on apple (*Pyrus malus* L.) tree trunks and fruit.

Materials and methods

The dendrometers (DEX70, Dynamax Inc., Houston, TX) are similar to Ceres dendrometers (Beedlow *et al.*, 1986; Thiede *et al.*, 1995; Link *et al.*, 1995), but are more flexible allowing for a greater change of thickness before physical resetting becomes necessary (Fig. 1). The dendrometer is constructed out of two aluminium bars attached to a flexible stainless steel band on which the strain gauges are attached. The flexible stainless steel band is 25.4 mm wide and 0.76 mm thick. The sensor is attached by screwing a bolt with a curved anvil at its end through one of the aluminium bars pressing the stem or fruit between two anvils (Fig. 1). Four strain gauges are connected in a full Wheatstone bridge arrangement and attached in the middle of the flexible band with two on each side. Dimensions of the device are given in Fig. 2.

Fine-wire copper–constantan thermocouples were appressed to the metal housing of each dendrometer to record sensor temperature. Thermocouples are not shown in Fig. 1. Air temperature was measured with fine-wire thermocouples at the same height as the apple with the dendrometer attached. As the stem or fruit diameter changes, differences in the relative tension experienced by the strain gauges are measured as a millivolt signal. Dendrometers and thermocouples were attached to a datalogger (CR7X, Campbell Scientific, Logan, UT) with data averaged over 1 h intervals for the first few days of observation and over 10 min intervals for the remainder. Millivolt signals are converted to millimeter units after calibration. This datalogger has a resolution of 0.166 μV over a full scale range of ± 5 mV.

Calibration was done on each dendrometer by altering the spacing of an internal micrometer and recording the millivolt signal. Diameters ranged from 0 to 12.7 mm. The calibration relation is linear and given by:

$$\mathrm{mm} = b_0 + b_1 \times \mathrm{mV} \qquad (1)$$

where b_0 is the intercept value (mm) when the millivolt signal (mV) is zero and b_1 is the slope of the relationship between diameter and millivolt signal.

A dendrometer was attached to an Invar metal alloy cylinder (diameter of 1.27 cm) to compute a practical operational error of the measurement system and to determine the relationship between millimeter units and temperature. Invar was used because it has a very low thermal expansion co-efficient (Katerji *et al.*, 1994) providing a stationary target for computating system error and temperature effects. A practical operational error of the measurement system, or repeatability, was computed by selecting a series of observations at near constant temperature. Fifty one observations were obtained over 4 d between 16 °C and 17 °C. The mean of these numbers was computed and reported with one standard deviation about the mean as the practical operating error or repeatability of the sensor.

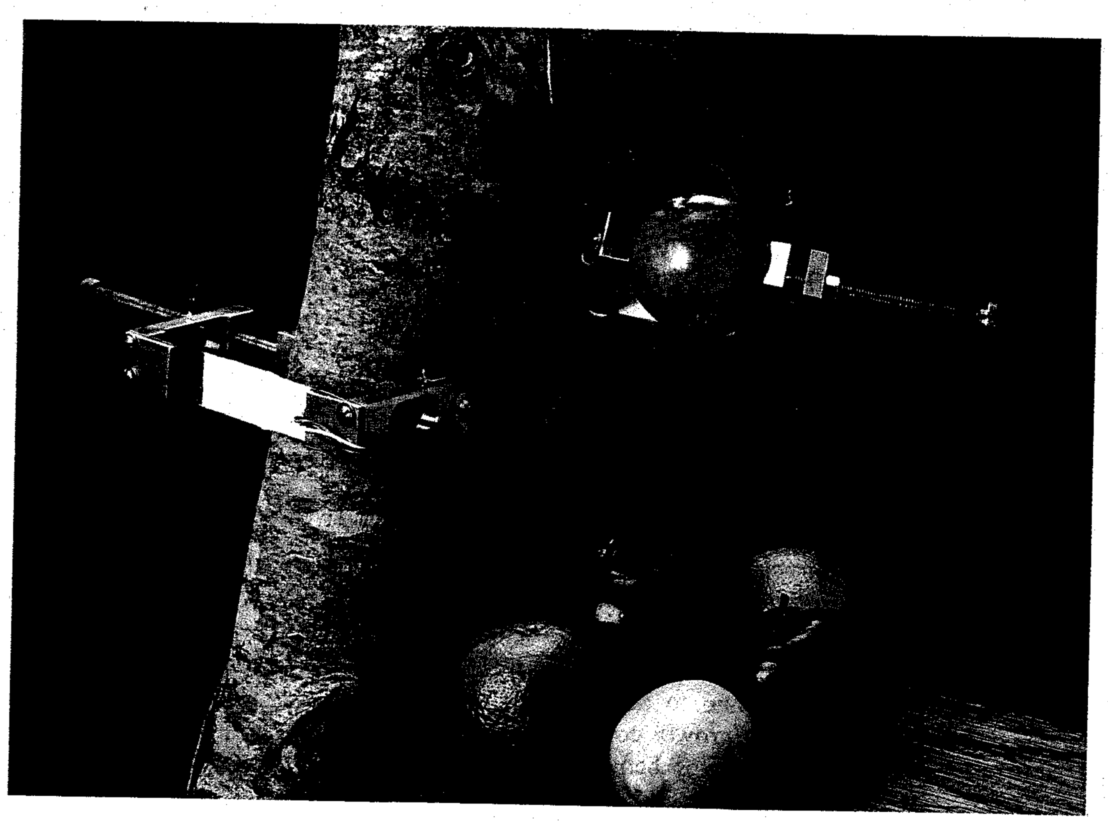

Fig. 1. The DEX70 dendrometer showing the aluminium bars and stainless steel band with attached strain gauges clamped on to an apple fruit and the larger, DEX100 dendrometer clamped on to a tree trunk.

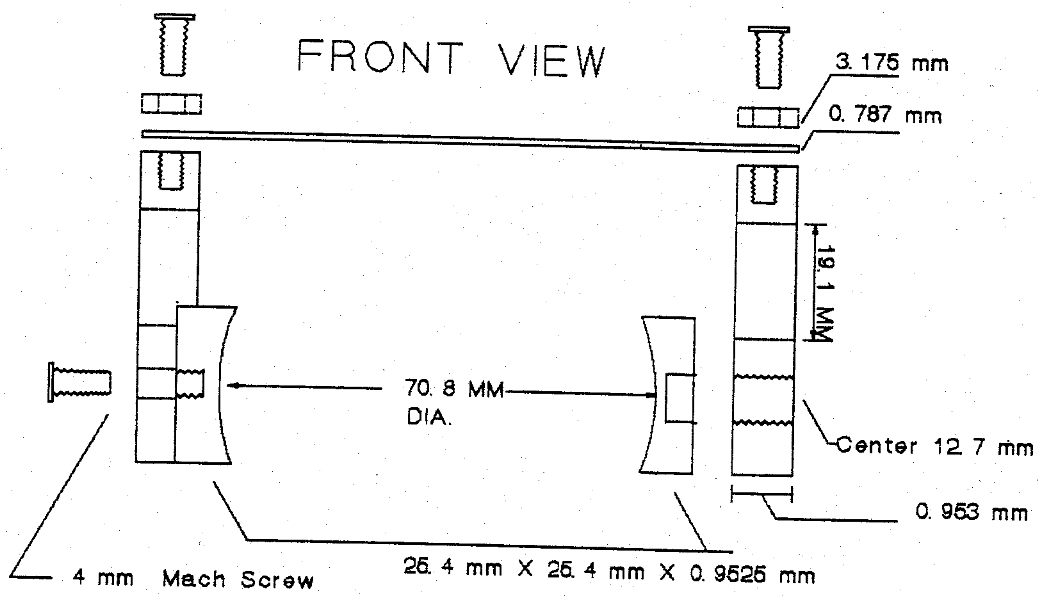

Fig. 2. Dimensions of the metallic pieces of the DEX70 dendrometer.

The effect of temperature on sensor signal after conversion to millimeter units was determined using a linear regression as:

$$\mathrm{mm} = b_0 + b_1 \times {}^{\circ}\mathrm{C} \qquad (2)$$

where b_0 is the intercept value (mm) when the temperature is 0 °C and b_1 is the slope of the relationship between diameter and temperature.

The field test was done in an apple orchard in Mattawa, Washington in September 1995. Two DEX70 dendrometers were attached to different tree trunks (diameters of 5 and 7 cm) and one was placed on an apple fruit (diameter of 6 cm). Data were acquired over a 15 day period, then transferred to a microcomputer for analysis. Millivolt signals were converted to millimeter units. The initial millimeter value of each dendrometer was then subtracted from subsequent values so that each unit started at zero. The effect of temperature was removed by predicting the effect of temperature on each unit using equation 2 and then subtracting this value from each observation. Values can be negative.

Analyses were done using JMP version 2.0.2 software (Sall *et al.*, 1991).

Results

The results presented include conversions from millivolt to millimeter units, temperature effects on the dendrometer using Invar metal, and time-course data on stems and fruit.

The relationship (equation 1) used for conversion from millivolt to millimeter units was linear over the 0–12.7 mm range and was highly significant ($F=46\,743$, $P<0.00001$, $R^2=0.9996$, $b_0=-0.312$, $b_1=4.499$).

The practical operational error or repeatability of the measurement system under the conditions of the test is given as one standard deviation (0.00947 mm) about the mean value of 3.68356 mm.

The relationship (equation 2) between sensor temperature and apparent thickness in millimeters was linear and highly significant ($F=392.5$, $P<0.00001$, $R^2=0.88$, $b_0=-0.0729$, $b_1=0.00296$, Fig. 3). On a typical day the temperature spread of 21 °C caused an apparent change of 62 μm. By applying equation 2 the temperature effect on the apparatus can be compensated, and the data expressed for constant temperature of 24.6 °C (Fig. 3).

The two sensors attached to stems measured diurnal change (thicker at night and thinner in the day) in thickness. This was similar for each stem and after temperature compensation typically ranged over 0.7 mm diurnally (Fig. 4).

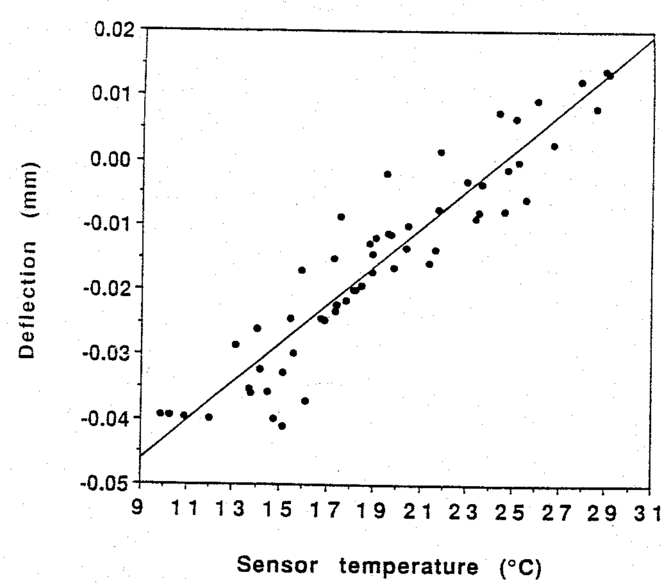

Fig. 3. Relationship between sensor temperature and DEX70 dendrometer deflections on a cylinder of Invar metal.

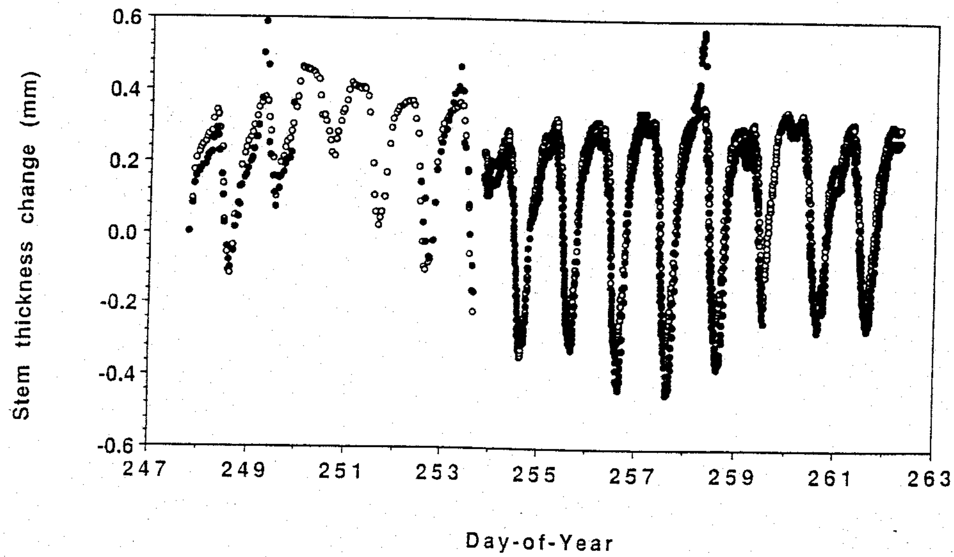

Fig. 4. Diurnal stem thickness dynamics on two apple tree trunks.

After temperature compensation apple thickness increased 3.3 mm over the 15 d period (Fig. 5). The increase in thickness was almost constant over the period with relatively little diurnal variation. There was a decrease in the rate of fruit thickening over days 254 to 258 and greater shrinkage during the daytime. These days had maximum air temperatures of 30–33 °C. Maximum temperatures before and after this period were less than 30 °C and coincided with less daytime shrinkage and higher growth rates.

Discussion

The objective of this study was to determine the operating characteristics of the DEX70 dendrometer in the field. The dendrometers were attached to apple tree trunks, fruit and Invar metal. The improvement over the dendrometer of Beedlow *et al.* (1986) is increased flexibility of the metal housing allowing measurement over a wider range of diameter changes without deforming the tissue.

The DEX70 dendrometer is more flexible than earlier versions made of solid polyvinyl chloride (Beedlow *et al.*, 1986) or solid aluminium (Thiede *et al.*, 1995) because the new dendrometer has a flexible stainless steel band upon which the strain gauges are attached. The calibration relationship between displacement and the millivolt signal is linear. Constantan–foil strain gauges are linear within ±5% strain (Schütte and Burger, 1981). In this test data acquisition began 3 months after calibration. It was assumed that the calibration relationship was stable over

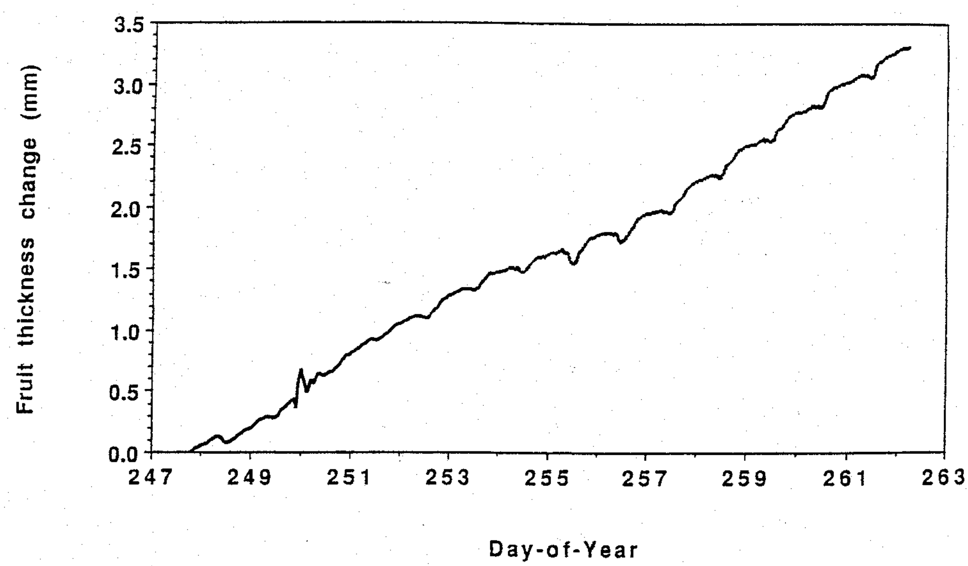

Fig. 5. Time-course of thickness increase on an apple.

this period. Long-term effects on materials can potentially cause a change in the relationship.

Under stable operating conditions of nearly constant temperature with the sensor on Invar metal random noise in the data was observed. In this test a value of 9.47 μm was determined as the practical operational error or repeatability of the sensor. This value is one standard deviation of the mean. This analysis is only relevant to a stationary target such as Invar that could be repeatably sampled. Living material is not stationary.

The effect of temperature on the sensor needs to be taken into account when collecting field data. The effect on the sensor ranged up to 62 μm for a temperature range of 21 °C. This effect, if unaccounted for, can cause up to 10% error based on the range of stem diameter observed (0.7 mm). This effect could be compensated for by application of equation 2. Others have considered temperature effects on plant material (Schütte and Burger, 1981). They note that there is no typical coefficient of thermal expansion for living material, but were able to elicit a thermal expansion in a 40 mm diameter tree. If care is taken temperature effects on stems can be held to less than 5% (Schütte and Burger, 1981). No attempt was made to account for thermal expansion in living material in this study.

Stems shrank during the day and thickened at night. This is a common response attributed to changes in hydration status of the tissues (Klepper *et al.*, 1971; Lassoie, 1979; Link *et al.*, 1995). The most interesting observation for stem thickness dynamics was the similarity between the data sets in Fig. 4. These two dendrometers were attached to trunks of different trees. The similarity in the diurnal magnitude of change suggests that both trees were experiencing similar water status conditions as is likely in an irrigated apple orchard. There was no evidence of growth in the stems over the 2 week period.

The fruit expanded 3.3 mm over the period suggesting that carbon is being allocated to the fruit during this time. The diurnal pattern in diameter indicates that the fruit lost water during the day. The shrinkage was greater on days 255 and 256 than other days. These two days were the hottest during the period suggesting that water loss was greater on these days. Berger and Selles (1993), in a similar study of peach fruit, conclude that water is lost from fruits by 'transpiration' and is not drawn out of the fruit back into the tree. Most of the water entering the fruit during the maturation phase is from phloem elements and not xylem. It is likely that apples behave as peaches and that shrinkage during the day is because of water loss by fruit transpiration.

In conclusion, the present study has demonstrated the use of a new dendrometer (DEX70) on apple stems and fruit. The relationship between distance and millivolt signal is linear. Temperature effects on the sensor can cause up to 10% error if not taken into account. This sensor has the unique characteristic of being sufficiently flexible for use on rapidly expanding tissues such as fruit, without frequent readjustment.

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