Microcomputer-based system for the measurement of transpiration rate in trees by the heat pulse method

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A microcomputer-based system was designed to measure water transport in trees by the heat pulse method. The system comprises a heater probe as a heat source and a thermistor, incorporated into a bridge which is automatically balanced by the microcomputer. The overall dynamic range of the system for temperature is 22 bits and the resolution for temperature determination is about 1.45×10^{-4} °C. The elapsed time between the heat pulse injection and the thermal peak at the thermistor is calculated by the microcomputer. The computation program includes algorithms for base-line slope correction and a noise immune derivative evaluating routine for peak recognition. The system was tested in the laboratory and in the field on a citrus tree.

INTRODUCTION

The transpiration rate of trees, which is a function of the sap flow rate in the stem, is an important parameter for understanding plant–water relations and could eventually help in devising effective and economical irrigation control systems. Among the possible methods for measuring sap flow, the heat pulse method[1] seems to be most suitable for field implementation by automatic methods. The technique involves the injection of a heat pulse into the stem and the measurement of the elapsed time until the resulting temperature peak is detected at a known distance upstream. The experimental methods used by researchers in the field to realize this measuring technique were based on manual operations, such as prebalancing of thermistor bridges and reading the elapsed time manually.[1] Albeit an important step in the evaluation of the measuring method, these experimental approaches are unsatisfactory when long-term measurements are attempted. Furthermore, potential application of this measurement in "smart" irrigation control systems will necessitate automatic data processing to produce a usable analog or digital control signal. The purpose of this study was to investigate the possibility of automating measurement of sap flow in trees by the heat pulse method and to identify the major instrumental problems that must be solved before such a system can be successfully applied in the field.

Although the present study was concerned with transpiration, the general design concepts could be applied in other areas when small temperature pulses are to be monitored and their peak time and/or height determined.

I. THEORETICAL CONSIDERATIONS

Based on previous investigations,[1] the heat pulse in the present study was injected by a line heater inserted radially into the stem and the temperature was sensed by a thermistor probe inserted into the trunk 15 mm upstream. The solution of the heat transport equation for a line source, assuming a two-dimensional heat flow, is given by Marshall,[2]

$$T = \frac{H}{4\pi\rho c K t} \exp\left(- \frac{(x - Vt)^2 + y^2}{4Kt} \right), \tag{1}$$

where: T = temperature elevation, H = heat output per unit length of heater, ρ = density of the xylem, c = specific heat of the xylem, K = thermal diffusivity in xylem, x = vertical distance between heater and thermistor, y = horizontal distance between heater and thermistor.

The temperature pulse reaches a maximum at time t_m (referred to as the time of injection of the heat pulse) from which the heat wave convection velocity V can be derived:

$$V = \frac{\sqrt{x^2 + y^2 - 4Kt_m}}{t_m}. \tag{2}$$

Hence, the convection velocity V can be determined assuming that t_m is measured and K, the diffusion coefficient, is known. The latter can be determined from a test run in early morning when $V = 0$:

$$K = \frac{x^2 + y^2}{4t_m}. \tag{3}$$

Alternatively, both K and V can be determined from the pulse shape of the heat pulse by solving two equations at two points of the pulse heat slope.[2]

A prerequisite for applying the method for calculating the transpiration rate from a measurement of sap velocity is the ability to reliably monitor the heat pulse in the field. Considering the fact that the temperature rise associated with the heat pulse could be 0.2–0.6 °C and temperature resolution near the peak of the heat wave should be extremely high, it is clear that the design of the signal processing system

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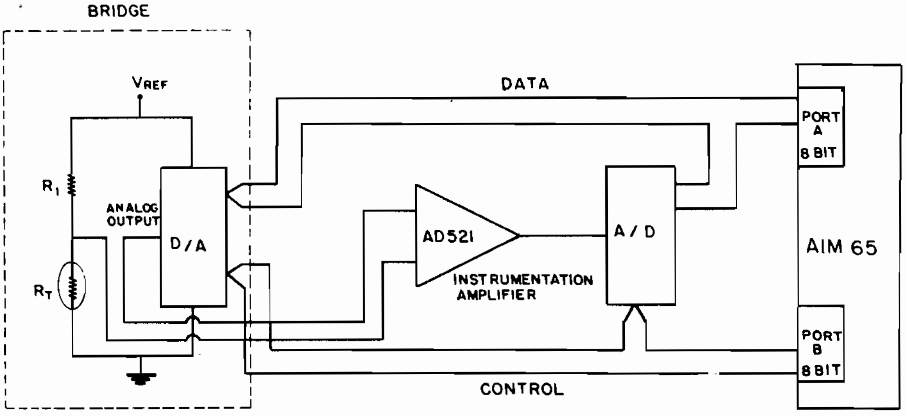

FIG. 1. Block diagram of the proposed system.

must permit the measurement of temperature variations on the millicentigrade scale. Furthermore, since the information is embedded in the elapsed time between the onset of the heat pulse and the temperature peak time sensed by the thermistor, the noise level must be small enough to permit reliable determination of the peak time. The required high dynamic range could theoretically be obtained by using a high-resolution analog-to-digital converter (A/D). However, since preliminary estimation indicated that the present application calls for a dynamic range of about 20 bits, a high-resolution A/D was excluded for economical reasons. The solution adopted in the present study for achieving a large dynamic range is based on a bridge-type operation (Fig. 1), which was completely automated by using a general purpose microcomputer. The microcomputer was also used to process the digitized signals to produce the desired information, i.e., the elapsed time between the injection of the heat pulse and the thermal peak time.

II. SYSTEM DESIGN

The system (Fig. 1) comprises a self-balancing bridge in which the thermistor's (R_T) voltage drop is compared to the output of a digital-to-analog converter (D/A). The difference is amplified by an instrumentation amplifier, fed to an analog-to-digital converter (A/D), and the digitized signal is read by the microcomputer which also controls operation of the D/A. The signal dynamic range actually achieved by the system is the sum of the bit resolutions of the D/A and the A/D. By using a D/A with a 10-bit resolution and a A/D with a 12-bit resolution, an overall resolution of 22 bits is reached. It should be emphasized that the present application does not call for high accuracy in the temperature measurements, since only the deviation from ambient temperature is important. The electronic circuit of the system (Fig. 2) was realized using standard electronic components. The A/D chosen (AD/7550) is a dual-slope-type converter which has the advantage, in this application, of smoothing out noise by integrating the input signal over a fixed period of time (40 ms). Further noise filtering was achieved by limiting the bandwidth of the instrumentation amplifier (AD 521) to about 10 Hz using external components. A filter for the power line frequency (50 Hz in Israel) was also included to further attenuate interfering noise.

Since the reference signal of the D/A was 2.5 V (Fig. 2), the step resolution of the bridge was about 2.4 mV. This corresponds to a temperature span of about 5° at 25°C for the thermistor circuit used. The sensitivity of the thermistor was about 48 mV/°C and since the gain of the instrumentation was 83.3 and the bit resolution of the 12-bit A/D amplifier was 0.57 mV, the overall resolution of temperature determination was about $1.4\times 10\times 10^{-4}$ °C per 1 bit of the A/D.

III. COMPUTATION AND CONTROL

The signal processing algorithm was designed to overcome two basic problems: base-line drift and interference of noise in peak recognition. The former had to be introduced to overcome errors due to heating or cooling of ambient temperature, which might result in an apparent shift of the peak. The problem was overcome by estimating the base-line slope prior to injection of the heat pulse and correcting the temperature reading by extrapolating the assumed linear base-line shift to the pulse period. The base-line slope was estimated by a linear least-square fitting routine implemented in BASIC.

The random noise, associated with the low-level signals, could severely interfere in the determination of the peak time if a simple two-point derivative scheme is used for peak recognition. It was decided, therefore, to use a modified algorithm for derivative computation which has a built-in noise averaging feature. The algorithm uses five data points to which a second-order polynomial is fitted by the least-square fitting method.[3,4] Using this method, the derivative is calculated to be

$$\left(\frac{dy}{dt}\right)_i = \frac{1}{10}(-2y_{i-2} - y_{i-1} + y_{i+1} + 2y_{i+2}). \qquad (4)$$

Initial bridge adjustment, estimation of base-line slope, peak recognition, and elapsed time calculation were controlled automatically by the microcomputer. A general outline of the computer program is depicted in the flow chart of Fig. 3. The program was written in BASIC and stored on a nonvolatile memory (EPROM) so there was no need to reload the program after turning on the microcomputer. BASIC language programming significantly simplified the programming effort. This approach was possible in the present application, despite the fact that computations were carried out

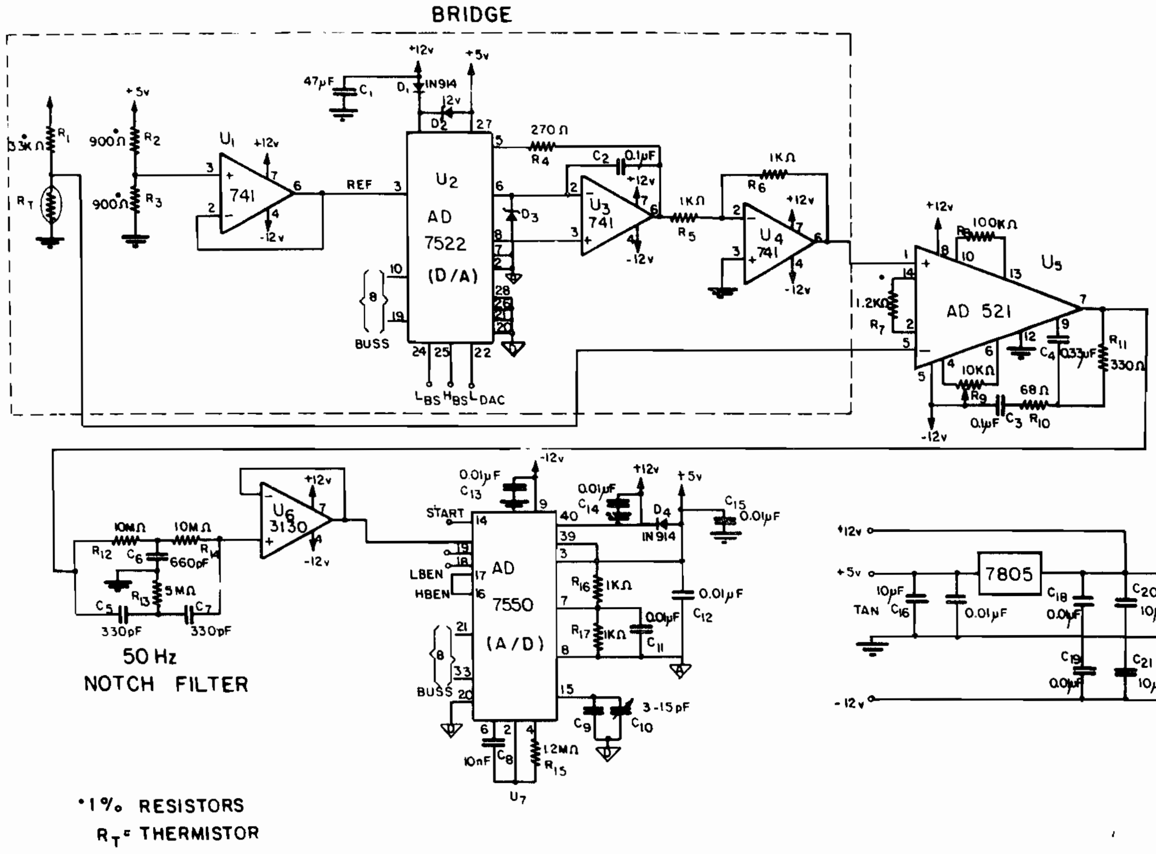

FIG. 2. Circuit diagram of the proposed instrumentation system.

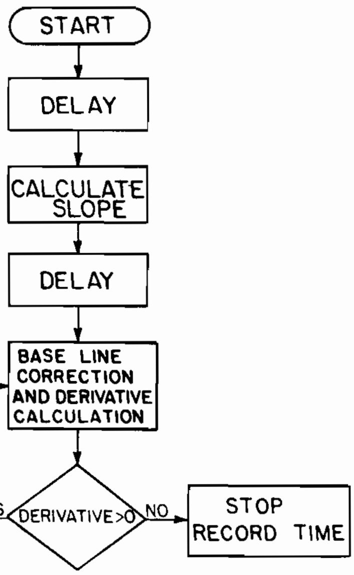

FIG. 3. Flow chart of main microcomputer program.

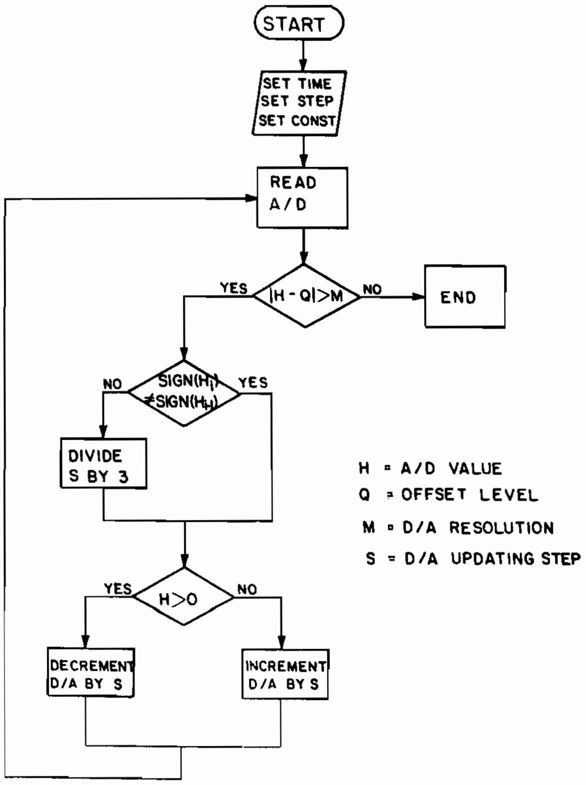

FIG. 4. Flow chart of computer program used in automatic bridge balancing.

on line, because the propagation velocity of the heat pulse is relatively low. The sampling rate of one sample per second used here, provided ample processing time in between the samples.

An efficient algorithm for the initial bridge-balancing operation was developed since the simple approach of a linear search for the balancing point was excluded on the grounds that it may require prohibitively long convergence times. For the 10-bit D/A used, a linear search may require up to about ~1000 steps which, at a rate of one sample per second may last about 16 min. The adopted search algorithm (Fig. 4) employs a variable step procedure in which the search is commenced with a large step, which is decremented by a factor of 3 every time the balancing point is past. The average number of steps until bridge balance was reached (to within the resolution of the D/A) was about ten steps.

IV. EXPERIMENTAL

A. Laboratory tests

The system was tested in the laboratory using a sinusoidal function generator to simulate the heat pulse signal. White noise was added to the simulated signal to examine the noise immunity of the algorithm. Base-line correction was tested by summing a ramp shape signal to the simulated heat pulse signal.

The system was also tested on a dry wood block of 100-mm diameter in which the thermistor probe and heat probe were inserted 15 mm apart.

B. Field tests

A citrus tree 22 yr old with a trunk diameter of about 200 mm was used in the field tests. The thermistor probe was inserted 10 mm below the cambium inside the trunk (the youngest xylem layer), 15 mm from the heat probe. The thermistor probe was connected to the instrumentation system described here and the data was printed out on the built-in printer of the microcomputer used (AIM 65: Rockwell International, Newport Beach).

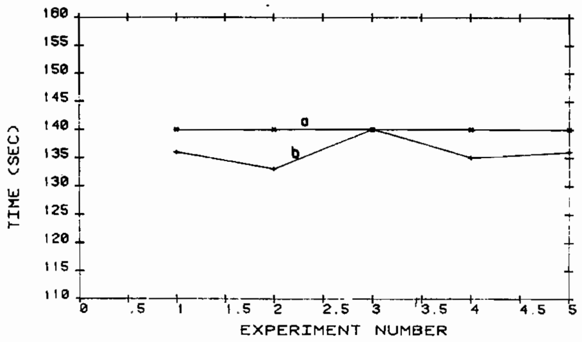

FIG. 5. Performance test with a noise-free simulated signal (a) and noisy simulated signal (b). The added noise level corresponds to a fluctuation of about 0.8°C with a 20-kHz bandwidth.

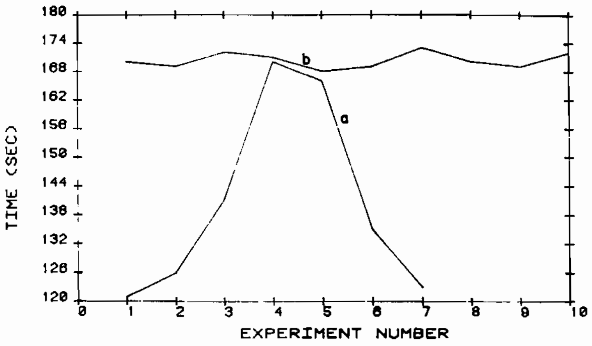

FIG. 6. Performance test on a dry wood block without (a) and with (b) base-line correction.

V. RESULTS AND DISCUSSION

Laboratory tests on simulated signal revealed that the basic accuracy of the elapsed time determination was 1 s for the range 10–320 s. The maximum error caused by adding white noise to the simulated signal was about 8 s for a simulated elapsed time of about 140 s (Fig. 5). The noise level added was 40 mV/rms (with a bandwidth of 20 kHz) corresponding to a temperature noise fluctuation of about 0.8°C (rms), which is much higher than expected in practice. The error due to a 10-mV rms noise was less than 1 s. This implies that the noise immunity of the system is ample for the present applications. Laboratory test runs on dry wood verified the simulated signal tests and demonstrated the importance of base-line correction. The base-line shifts in the experiments were probably due to two effects: a change in the ambient temperature and residual response of previous experiments. The latter was very significant, as the thermal time constant of the dry wooden block was found to be in the hours scale and the repeated pulse heat tests caused relatively large temperature drifts. Under these conditions, the base-line correction algorithm dramatically improved the accuracy of the elapsed time determination (Fig. 6).

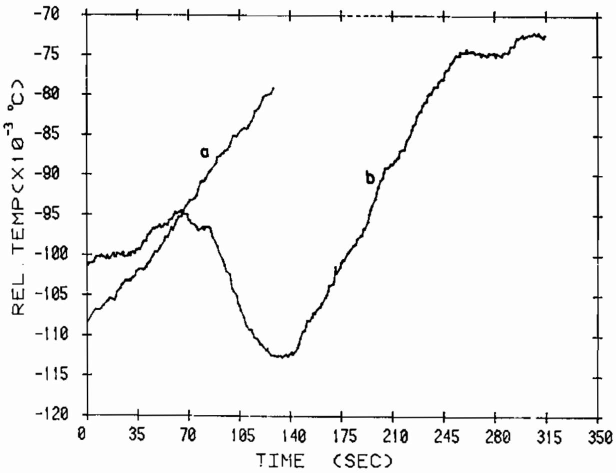

FIG. 7. Thermal base-line shift in citrus tree at 6:29 a.m. (a), and at noon (b).

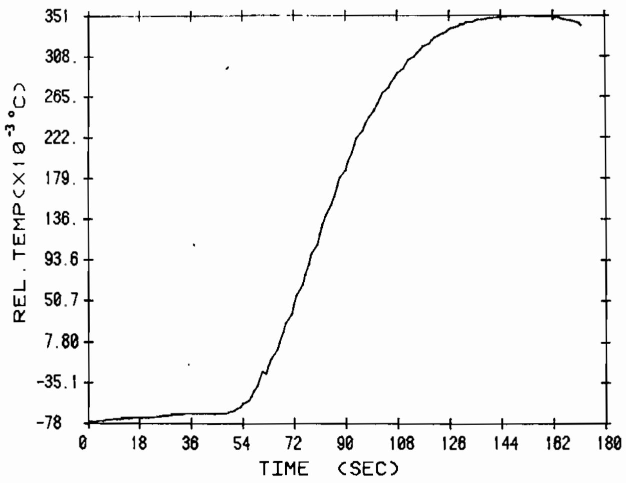

FIG. 8. Thermal heat pulse in citrus tree as recorded by system at 6:33 a.m.

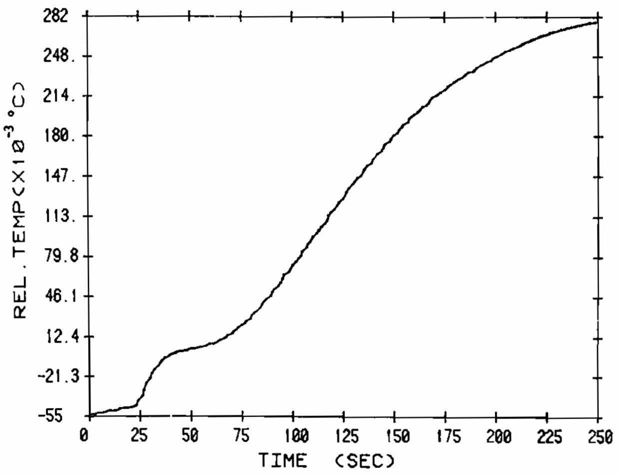

FIG. 9. Thermal heat pulse in citrus tree as recorded by the system at 12:12 p.m.

The base-line drifts in the early morning and at noon (Fig. 7) were of the order of 20 m°C/100 s. The base-line drift at noon was more erratic—perhaps due to incidental winds. Consequently, the automatic base-line correction may not have functioned in an optimal way since it assumes a constant base-line slope. Actual heat pulse records (Figs. 8 and 9) showed that base-line variation, probably due to external thermal interferences, could pose a problem. The hump at the foot of the heat pulse (Fig. 9) was evidently due to temperature fluctuation resulting from some external disturbance.

Time lapse measurements on the citrus tree at 6:47 and 7:04 a.m. yielded the value 221 s, which is primarily due to the diffusive transport. This value was shorter by about 10% than the time measured by an instrument that employs analog differentiation and zero crossing detector to measure the elapsed time (Y. Cohen, unpublished). Examination of the recorded pulses seems to indicate, however, that the results of the present system are more reliable. Although an assessment of the measurement accuracy and the influence of base-line fluctuations has not been made as yet, it is evident that more sophisticated signal processing may be required to further improve the overall accuracy of the system. A possible approach would be to fit the recorded heat pulse to a model pulse shape and to restore the base time from the residuals. This procedure, however, may necessitate the application of a more powerful microcomputer and probably ASSEMBLY language programming.

Notwithstanding the present signal processing limitation in terms of base-line fluctuation interference, the proposed system hardware and electronic circuit approaches seem to offer a good solution to the problem at hand. Although tested as yet in a single-channel operation, standard multiplexing techniques will enable the system to service a large number of trees as may be required in the envisioned research and agricultural applications.

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