Control Systems-based design of a plant intracellular pressure measurement instrument

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Abstract: - Cell turgor (plant intracellular pressure) is a parameter very known by the physiologists and its determination is fundamental for the evaluation of water relations of higher (multicellular) plants. It is largely used in studies of plant tolerance or resistance to various stresses caused by irregular supply of nutrients, water and some other factors required by plant organism. The determination of cell turgor is also important for the development of models for water transport in plant tissues. Although this matter is of great importance to the physiologists, there are a few papers describing realistic techniques for this purpose. Basically, the most reliable developed devices consisted of a capillary filled with oil. It was used to puncture a plant cell and the meniscus moved itself according to the intracellular pressure. A hydraulic apparatus driven by a DC motor was used for counteracting the cell pressure, impelling pressure in the sense of the plant cell. The effort dispensed by the motor was correlated with the cell pressure. In a previous paper we have applied by the first time a control systems approach to this problem. It was possible to determine the feasible work ranges, stability conditions, and performance. The hydraulic system plus the DC motor was changed by external controlled temperature acting over the capillary wall. However the meniscus position detection was exposed to ambient temperature causing noisy measurement. In order to overcome this problem we propose in this paper a new design based on Linear Quadratic methods, specifically Proportional plus Integral Estimators in conjunction with Proportional Plus Integral State Feedback Regulator Designs. Main idea is to profit by the robustness characteristics of a PI controller together with the setting of the filter bandwidths for good noise filtering and transient responses. Moreover, PI estimator can be optimum for a plant process noise which is high in intensity at low frequencies. The system was modeled and simulations were performed using parameters in limit conditions either of stability, or performance. Even in these conditions the responses showed high robustness due to large plant parameters variations and a reasonable noise filtering. Responses fails when the dead time, due to sample-hold circuits, optical sensor, and computer tasks, is increased. Limiting value found for the parameter was 0.2 second. It is sufficient to degenerate the system performance. Implications in to lower the dead time are related to rising the costs of the instrument. More expressive results are outlined in graphics followed by discussions.

Key-Words: - PI controller, pressure probe, turgor, intracellular pressure, measurement, LQR, LQG

1 Introduction

Cell turgor (plant intracellular pressure) is a parameter very known by the physiologists and its determination is fundamental for the evaluation of water relations of higher (multicellular) plants. This parameter is largely used in studies of plant tolerance or resistance to various stresses caused by irregular supply of nutrients, water and some other factors required by plant organism. The determination of cell turgor is also important for the development of models for water transport in plant tissues. Although this matter is of great importance to the physiologists, there are a few papers describing realistic techniques for this purpose. The most reliable method used was the pressure probe developed by Hüsken *et al.* (1978) to measure its value in a cell. Basically, the device consisted of a microcapillary which was introduced into the cell, a pressure chamber containing the pressure transducer, and a motor-driven metal rod which was used for changing the volume of the pressure chamber. When the microcapillary was introduced into the cell, the turgor pressure compressed the silicon oil filled into the whole device. In this first piece of equipment a silver wire was introduced close to the tip of the microcapillary, and after being supplied by a DC voltage, the electric resistance of the wire through the cell was measured, increasing considerably its value when the oil covered the wire, this is, the resistance value depended on the position of the meniscus (oil/sap boundary). This was used to feed back the system in such a way to drive the motor and to adjust the meniscus back to the original position (when the oil just covered the wire). The turgor pressure was obtained by the registering of the control effort dispensed by the motor. Some technological advances were introduced by Cosgrove and Durachko (1986), Büchner *et al.* (1987), and Nakahori *et al.* (1990), by means of an optical detection of the meniscus position either using a fiber optic sensor, or a Charge Coupled Device (CCD). Despite of the technological advance obtained on each work, there is not any commercial instrument for this purpose. The aim of this paper is not to discuss the reasons of the absence of this piece of equipment regarding to commercial aspects, but if one wants to develop such a instrument, probably, one will find a few details. With respect to the covered literature, some characteristics are common to all papers: none methodology about the design of each instrument was detailed. This lack of methodology is sufficient to lead to a more expensive design, even if the intention is the simple reproduction of the developed instruments. In a recent paper, Bertucci Neto et al. (1998) proposed a system for measuring cell turgor presenting some innovations such as the exclusion of the motor and pressure chamber apparatus and the inclusion of thermal compensation of the meniscus position, in order to reduce costs. It was also pointed the closed loop characteristic of the equipment leading to a control systems approach, permitting more precise answers on questions related to the performance of the instrument, and feasible work ranges. They presented a simple model to establish control conditions for the regulation of the meniscus position, which showed the possible work ranges of the system, such as necessary optical gains, maximum value of power supply, time constants, and coefficients. Despite of the control systems approach used in that paper to seek for a more rational design, an unsatisfactory aspect of the modified system was not predicted. It is a noise signal appearing in the optical sensor apparatus due to abrupt movements of the meniscus. Classical control systems methods such as applied in the previous paper do not deal with this kind of signal. To overcome this problem we present in this paper an improved design of the controller based on Proportional plus Integral State Estimate Feedback. Although the complexity of the design is increased we see by applying these concepts that the flexibility of the design is also increased.

2 Problem Formulation

The working principle of the pressure probe is simple. In concept it is like a miniature thermometer opened at the extremity that punctures the plant cell. After the cell puncture, the intracellular pressure pushes the liquid in the capillary, and the temperature must be raised up to the meniscus returning to its original position. The construction of the thermometer is also simple. A glass capillary is pulled to a fine point, filled with silicone oil, and an electric resistance covers all its extension. Certainly, difficulties at this point are in the maintenance of a standard capillary. A chamber filled with water and ice keeps the temperature at zero degree Celsius, and the meniscus lies near the tip of the capillary, out of the chamber. A power DC supplies the electric resistance till the oil temperature rises, so the meniscus moves back to the original position. The movement of the meniscus is observed through a microscope, under proper illumination. Based on the above described it is possible to take manually some measurements such as pressure and temperature versus voltage supplied, and then to proceed the calibration of the system. Automation procedure implies in the registering of the meniscus position compared with the considered origin, followed by a command that will regulate the output power of the DC supply. The open loop system can be represented by the following equation:

$$X(s)= (s+1/\tau)^{-1}(k_1 P_{ow}(s) - P_r(s)) \qquad (1)$$

Where X(s) is the position of the meniscus (meter); τ is the time constant of the thermometer; $P_{ow}(s)$ is the power that supplies the resistance (watt); $P_r(s)$ is the unknown pressure (N/m^2); and k_1, k_2, are conversion constants. Figure 1 shows the block diagram of the control systems problem to be analysed, where it can be distinguished the pressure input, the plant system (first term of equation 1), the optical sensor, and the controller blocks. There is also an input R(s)=0, representing the meniscus position referred to the considered origin, and an input W(s) representing disturbances due to the optical sensor and ambient temperature acting at the capillary tip. This last assumption is easily verified during the experiments and a preventive analysis is necessary. By means of the microscope, or the video monitor, the disturbance appears to be a sequence of positive and negative pulses, with low frequency (about 1 Hz) and low amplitude (up to 10^{-3}m). In the paper of Bertucci Neto et al. (1998) the thought control systems approach was a regulator with a Proportional-Integral-Derivative controller (PID) cascaded with the plant system. Settings of the PID were Ziegler-Nichols ruled. However there were not any mention about the control effort of the manipulated variable $P_{ow}(s)$, this is, it must be clarified if the control effort is physically realist. Another proposed question is how to minimize the effects, or even evaluate them, with respect to stability, performance, and accuracy. Finally, the maximum time spent for the determination (either by computer tasks, or even by digital/analog circuits) of the meniscus position is indubitable an important parameter.

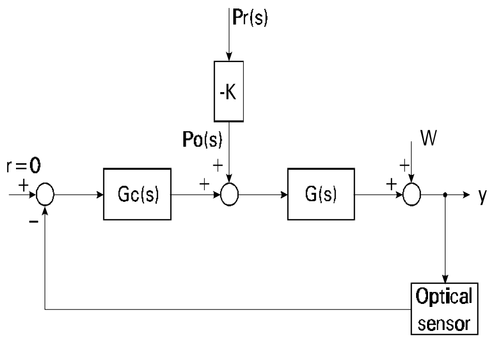

Fig.1. Block diagram of the closed loop system

3 Problem Solution

While classical control methods are executed generally in the frequency domain, with compensators designed to appropriately frequency-shape the return difference, or open-loop gain, linear quadratic methods are in essence time-domain methods (Anderson and Moore, 1989). By blending classical and linear methods it is possible to apply optimal gain constants allied with the filtering of undesirable resonant peaks, or high energy frequency bands in the power spectral density. Based on this, we used a frequency-shaped design approach, specifically, Proportional plus Integral Estimators in conjunction with Proportional Plus Integral State Feedback Regulator Designs. Main idea is to profit by the robustness characteristics of a PI controller together with the setting of the filter bandwidths for good noise filtering and transient responses. Moreover, PI estimator can be optimum for a plant process noise which is high in intensity at low frequencies.

The controller configuration can be abstracted from Figure 1. PI estimator has the input of the plant, and also the output Y as inputs, providing an output Ye as estimated Y. In the sequence, the output of the estimator Ye feeds the PI filter, whose output feeds back negatively the input related to the temperature over the capillary. The unknown pressure P_r was considered as a disturbance input, and by registering the voltage applied to the electric resistance (which realizes the control effort for returning the meniscus at the original position) we have the measurement of the pressure. Performance indexes associated to the estimator and regulator design were chosen to equally penalize input and output. PI constant gains (estimated and regulator design) were found in magnitude of 10^4. Simulations were performed in the sense of to analyze rise time, and time spent up to the steady state condition be reached, due to an input step at the reference R, offset errors that appear during dynamic regulation, and power spectral density to prevent undesirable resonance frequencies. These parameters were also simulated in different conditions of sensor noise (input W in Figure 1) and dead time T, included in the model as a sample hold block. Sensor and process noises were considered as uncorrelated Gaussian noise. Finally, after choosing the limit settings for the augmented system, it was investigated its robustness due to changes in the plant system parameters.

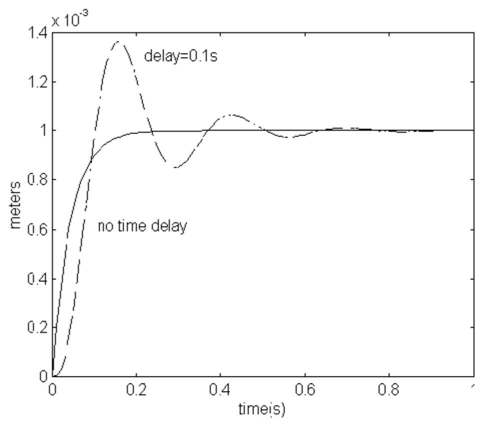

Fig. 2. Output Y Response due to a 10^{-3} m step applied to the regulation R input. Controller gains are optimums. Solid line curve: response with no delay time. Dashed curve: response after inclusion of a time delay equal to 0.1 second.

We begin the explanation through the information presented in Figure 2. Solid line curve is the response due to a 10^{-3}m step applied at the input R, with no delay time, while the dashed line curve is the response due to the same step but in the presence of 0.1 second dead time. As expected, solid line curve shows a smaller rise time of 0.08 second comparing to the time constant of the plant system (τ=1 second), and also a smaller error time (near 0.2 second in the 1% accuracy band). This happens because the proportional and integral gains (Kp, Ki, Kep, Kei) obtained from linear quadratic method, and linear Gaussian method, respectively, are optimums. However, the inclusion of a 0.1 second dead time makes things worst, rising the error time up to 0.7 second in the 1% accuracy band. Moreover, if the dead time is increased to 0.26 second the system oscillates. By this reason, we consider a dead time equal to 0.2 second the maximum allowable.

Figure 3 shows a fictitious signal attributed to the pressure input Pr. This signal is composed by steps, positive ramp, and negative quadratic ramp, added to a Gaussian noise. As we can see, despite of the long time taken (1000 seconds), the signal contains high frequency components.

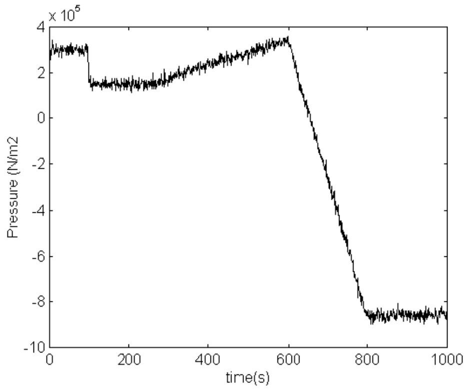

Fig.3. Fictitious signal used for the pressure input, containing Gaussian noise.

If we apply the signal showed in the Figure 3 to the pressure input, we have an unexpressive background response, showing a very good dynamic regulation. But this occurs in the absence of dead time. How the worst case was found to be a 0.2 second dead time, we must investigate the behavior of the regulated output. Keeping the same values for the gains, this is, Kp=Ki=Kep=Kei=4.0.10^4, and keeping the maximum allowable dead time, we obtain the signal at the output of the system as shown in Figure 4. In this figure it can be viewed a background noise presenting 99% of the pulses inside of the +/- 4.0.10^{-5} band. Obviously this error is transferred to the controller and translated into control effort for the regulation. Remaining peaks are clearly due to abrupt changes in the pressure signal. This result indicates that if we apply a pressure signal corresponding to 10^{-3}m the maximum error is +/- 4%. Obviously if the dead time is smaller the error is also smaller.

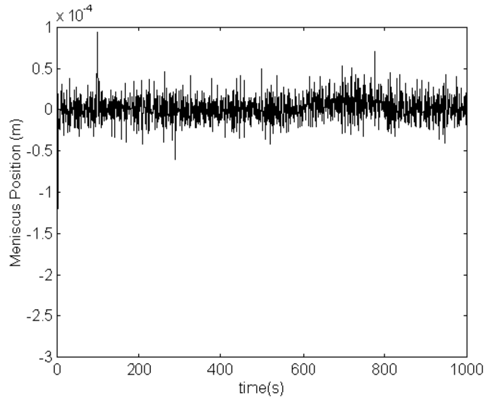

Fig.4. Regulated output signal due to the pressure input signal as the same manner as Fig.3.

Know, if we try to better this response changing the gains of the controller, it is adequate to investigate the power spectral density. For instance, if the need is to decrease the rise time, one could decrease the proportional gains, keeping the integral gains as the same. However this could not be an adequate choice. This situation is depicted in the Figure 5, where the proportional gains Kp and Kep were decreased to 10^3. The signal applied is the same as shown in the Figure 3, without the Gaussian Noise. We see all the power spectral density to be increased, specially in the 0.1Hz to 0.3Hz band. Pointed this, it must be investigated if the resonant frequency favors, or not, noise filtering, system dynamics, and control effort.

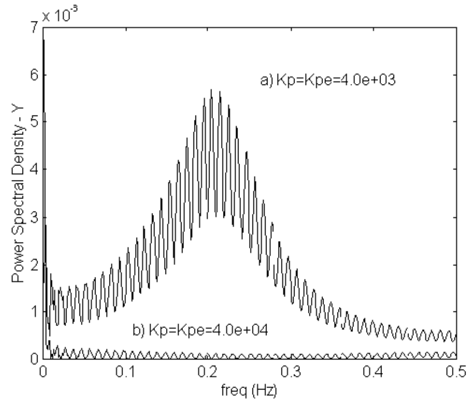

Fig.5. Power spectral density of the output signal due to pressure input signal as in Fig.3, without Gaussian noise. Curve a): Kp=Kep decreased to 4.0.10^3. Curve b): Kp=Kep= 4.0.10^4.

When we test the system robustness due to plant system variations keeping the parameters values equal to Kp=Ki=Kep=Kei=4.0.10^4, 0.2 second dead time, and a noisy signal as shown in Figure 3, the regulated output shows a quite imperceptible variation, this is, the result is similar to that exhibited in the Figure 4. Plant system parameters were varied from –50% to +100%.

4 Conclusion

By means of Proportional plus Integral Estimators in conjunction with Proportional Plus Integral State Feedback Regulator Designs, it was possible to design a controller that responses in satisfactory way to noisy signals. Even in the considered dead time limit, simulations indicated Time spent in data acquisition and computer tasks, represented by the parameter dead time, appears to be highly significant. First, because it has direct influence in the performance and accuracy of the system, and second, if it is larger than 0.25 second, the output signal will oscillate. The importance in to decide which is the design appropriate value of the dead time is related to the costs of the optical sensor device plus the data acquisition system. In the practice, it was experienced by means of less expensive devices that the time spent only in the meniscus position calculus routine had the duration of about 0.3 second, getting unrealizable what was proposed in this paper. If the purpose is do lower the spent time at reasonable low costs then another techniques must be investigated, such as linear photodiode array detection, or video line discrimination. Despite of the increased complexity in the design, it showed to be useful for practical implementations.

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