Experimental Tests of Digital Filters for Control of a Pilot-Scale Batch Distillation Column

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Abstract

Measurement signals that a computer uses to take control actions are usually contaminated by noise. The presence of noise is undesirable because it may be detrimental to the operational control. In order to reduce the noise level in a batch distillation column control loop, two digital filters were experimentally tested: the double exponential filter and the moving average filter. The runs have shown how important the choice of the digital filter is to achieve a good control performance. For control tasks, this choice must be a compromise between data smoothing and the ability to respond rapidly to real changes in the process.

1. Introduction

Due to the cost reduction in microelectronic devices and the benefits gained from automation, the use of digital computers for industrial process control has become attractive.

When a digital computer is applied for control, the process is observed with sensors which convert physical variables into electrical signals. The continuous measurements are then converted into digital form by an analog to digital converter and processed by the computer. The measurement signals are usually contaminated by noise.

The term "noise" may be defined as those fluctuations in the process signal that do not contain useful information. It causes a degradation of control performance and may arise from several sources: the measurement device, electrical equipment or the process itself. Noise reduction may be accomplished by analog and/or digital filtering.

In processes where the presence of noise may not be neglected, one of the steps to digital control implementation consists in the choice of an appropriated digital filter. A good digital filter should let the relevant information pass through and block the noise. Many articles report the application of digital computers in process control, but they do not mention digital filtering issues.

The present work discusses the influence of digital filtering on the control of a pilot-scale batch distillation column to separate ethanol/water mixtures. Two important types of low pass digital filters, the double exponential filter and the moving average filter, were experimentally tested and compared. These filters were used in two control strategies: a self-tuning regulator (STR) with variable forgetting factor and a feedforward controller (FC) based on the mass balance between the top and bottom of the column, which were presented by Oisiovici *et al*. (1998). The control objective was to keep the distillate composition (controlled variable) constant at a desired value by varying the reflux ratio (manipulated variable).

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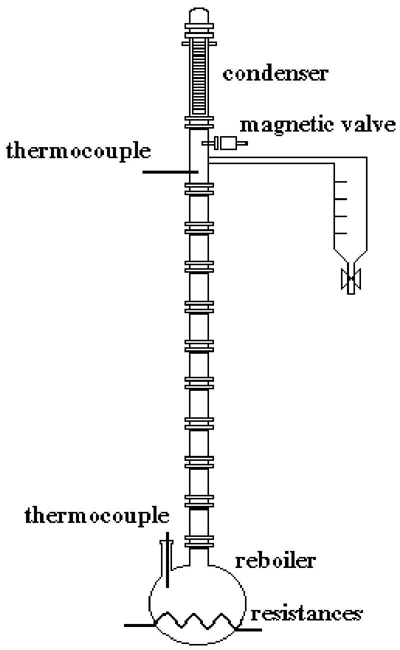


Figure 1. The batch distillation unit

2. Experimental Apparatus and Control System

A 40 mm I.D. batch distillation column consisting of ten sieve trays was used in the experimental studies (Figure 1). A 5 litre glass still is heated by three resistances, providing a maximum heating power of 2000 W. The overhead product is totally condensed in a vertical heat exchanger using cold water and there is no reflux drum. The desired reflux ratio is set by a magnetic valve which alternates from the distillate position to the reflux position in appropriated time intervals. The top column and still temperatures are measured with thermocouples.

A PC monitors and controls the operation. At each sampling period, the computer sends a digital signal to select the top or bottom thermocouple channel. The analog output signals of the temperature sensors are amplified, converted to digital signals and read by the CPU. A digital filter is implemented to reduce noise, as it is shown in Figure 2. The temperature of the vapour leaving the top plate is used to infer the vapour composition and this value is equal to the distillate composition (total condenser). The same procedure is used to infer the still composition. The acquired data are used to calculate the reflux ratio to keep the distillate purity at the set-point. A digital signal sent by the computer controls the position of the magnetic valve according to the previously calculated reflux ratio. A 10s sampling period was found to be the optimal.

Initially, the column was operated at total reflux until the hold-up on the plates was established and the column was brought to equilibrium. Then, the reflux ratio was automatically set to a minimum value previously chosen. When the distillate product withdrawal began, its composition was usually above the set-point and the reflux ratio calculated by the controller was found to be lower than the minimum. In this case, the reflux ratio was kept constant. Control actions began when the top composition approached the set-point.

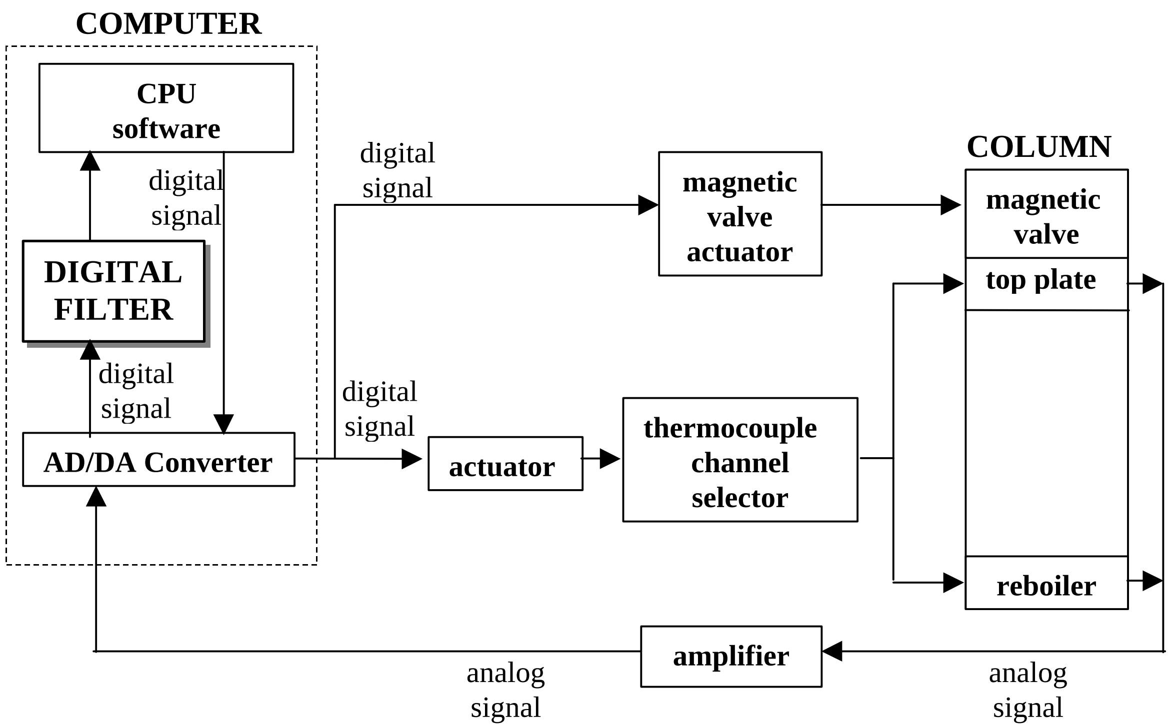


Figure 2. Digital filtering in the automation and control system

3. Digital Filters

Two digital filters were implemented:

3.1. Double Exponential Filter

The double exponential or second-order filter is equivalent to two first-order filters in series. The advantage of the double exponential over the simple exponential one is that it provides better filtering of high-frequency noise.
The double exponential filter is defined by:

$$Y_n = \alpha^2 X_n + 2(1-\alpha)Y_{n-1} - (1-\alpha)^2 Y_{n-2} \qquad (1)$$

where $0 < \alpha < 1$. When $a \to 1$, the filter output tends to the measurement X_n and when $a \to 0$, the current measurement tends to be ignored.

3.2. Moving Average Filter

The moving average filter averages a specified number of pasta data points by giving equal weight to each point. The recursive form of this filter is:

$$Y_n = Y_{n-1} + \frac{1}{J}(X_n - X_{n-J}) \qquad (2)$$

In this work, X_n is the digital equivalent form of the electrical signal generated by the thermocouple. A detailed description of both filters is given by Seborg *et al.* (1989).

4. Results and Discussion

In order to study the influence of α on the control performance, some runs were carried out varying this parameter. The results for the self-tuning regulator (STR) are shown in Figures 3 (a) and (b) and in Table 1.

The narrowest range of the deviation variable y^* was obtained when α was 0.5. For α = 0.7 (Figure 3a), there was a poorer reduction of noise and the behaviour of the controlled variable was more oscillatory. A smaller value of α (α = 0.3) reduced the noise greatly, but the filter was sluggish and not suitable for control tasks (Figure 3b). The best value of α was found to be 0.5 and it was used in the rest of the runs.

α	y^*
0.7	$-0.056 < y^* < 0.108$
0.5	$-0.038 < y^* < 0.032$
0.3	$-0.084 < y^* < 0.057$

Table 1. Influence of α on the STR's performance

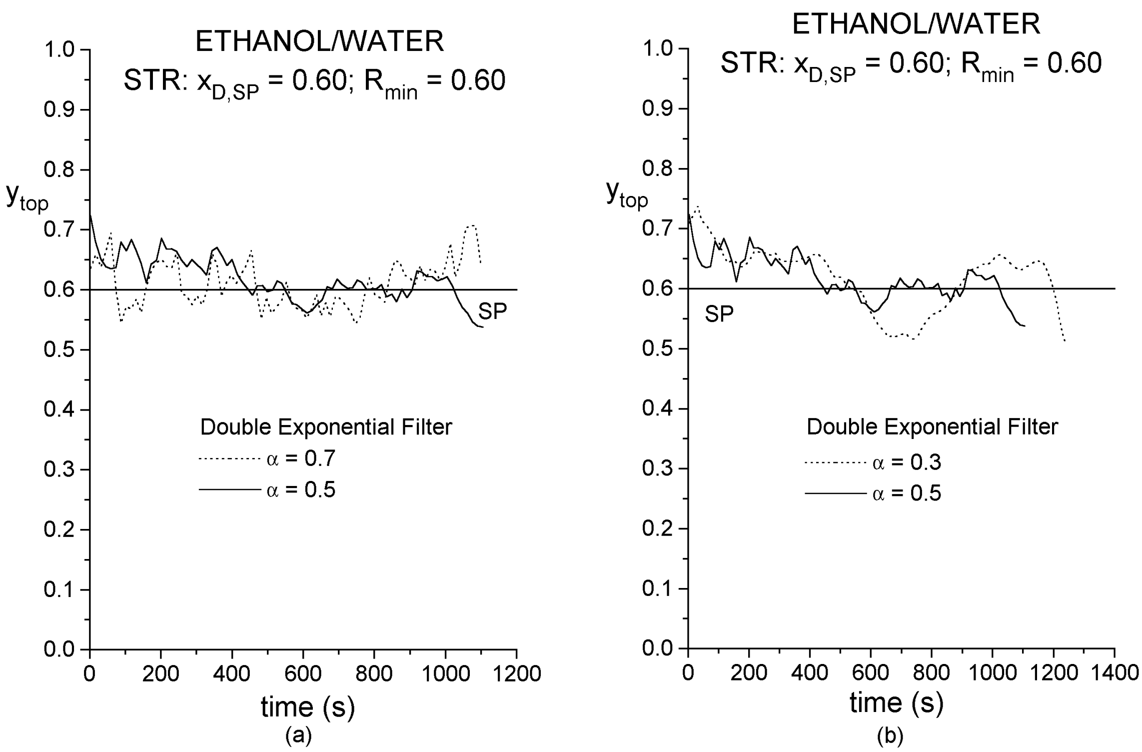
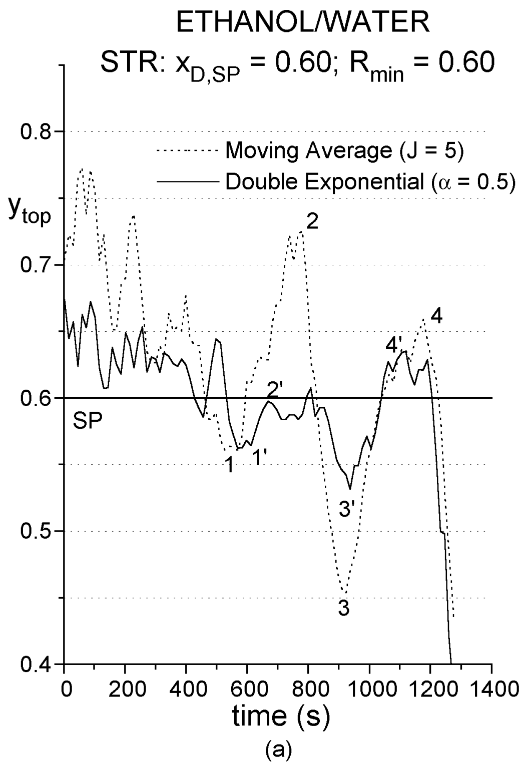


Figure 3. Influence of α on the STR's performance



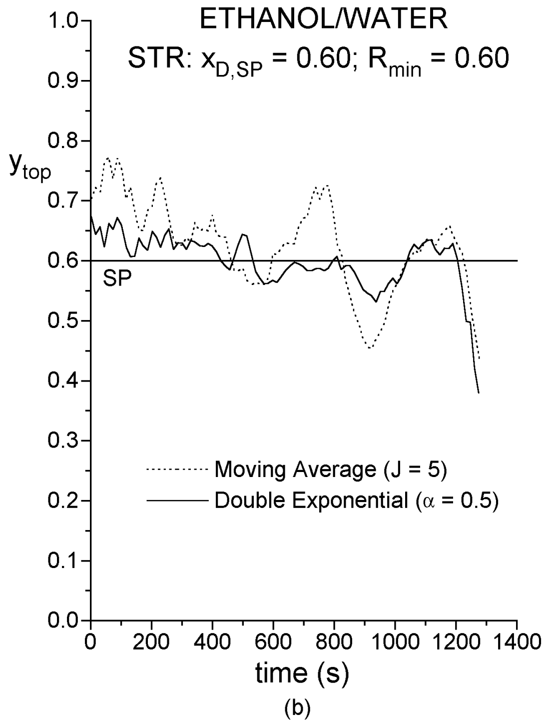


Figure 4. Comparison between the moving average and the double exponential filter (STR)

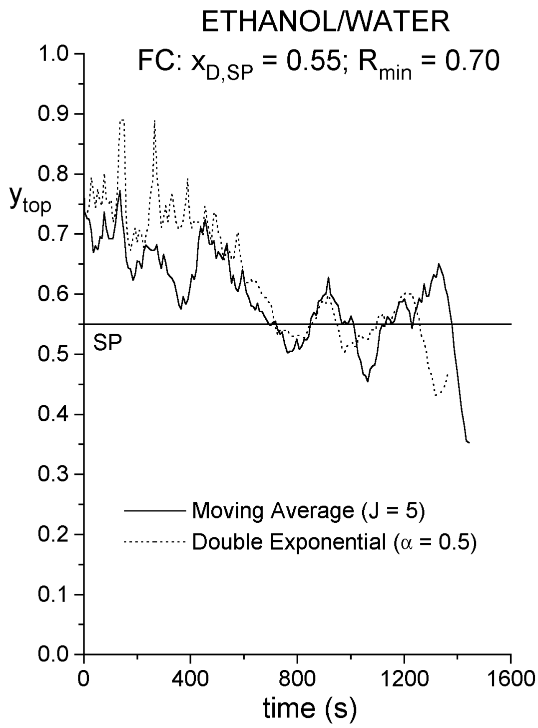


Figure 5. Comparison between the moving average and the double exponential filter (FC)

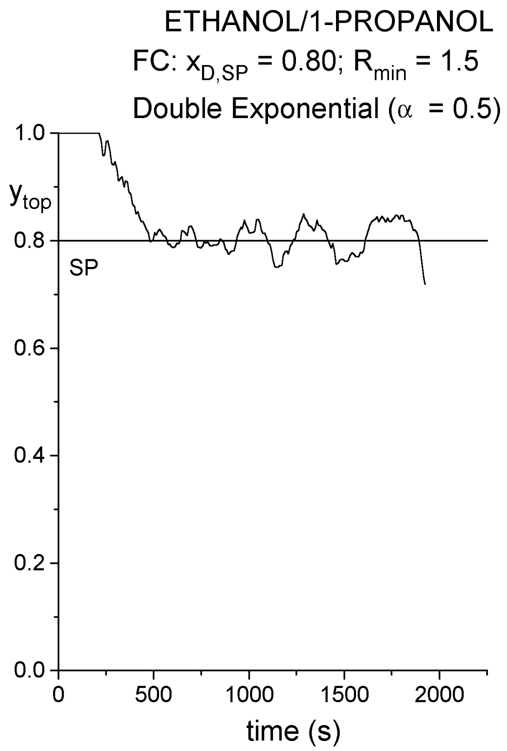


Figure 6. Batch using the double exponential filter with $\alpha = 0.5$ (ethanol/1-propanol)

Figures 4 (a) and (b) compare the double exponential filter with $\alpha = 0.5$ and the moving average filter with J = 5. When the moving average was applied, the profile of y_{top} was smoother but the peaks were greater (as it is shown by the corresponding peaks 1-1', 2-2', ...), indicating that the control actions were more delayed. The filter does not react adequately to real changes, what is detrimental to the control performance. The same conclusions were obtained when the batch distillation was controlled by the feedforward strategy (Figure 5).

Figures 3, 4 and 5 also show that a higher level of oscillations was present when the composition of the vapour leaving the top plate (y_{top}) was above 0.6, i.e. approaching the azeotrope composition. This happens mainly because of the thermodynamic properties of the ethanol/water mixture and it does not depend on the filter choice. In the region near the azeotrope the behaviour of the ethanol/water system is such that a change in temperature from 79.30 to 78.15 ^{o}C corresponds to a change in the ethanol composition from 0.5732 to 0.8943. Once the precision of the temperature was $\pm$ 1^{o}C and the composition is too sensitive to temperature changes in that region, accurate values of y_{top} could not be obtained since the compositions were inferred from temperature measurements.

When experiments were carried out with the ethanol/1-propanol system, which has very different thermodynamic properties, this problem was not observed, as it is illustrated in Figure 6.

5. Conclusions

In order to reduce the noise level in a batch distillation column control loop, two digital filters were experimentally tested: the double exponential filter and the moving average filter.

In the double exponential filter, as the parameter α increases more weight is given to the current measurement. At high values of α, there is a poorer reduction of the noise level but the filter tracks real signal changes more easily. When α is small, the double exponential filter reduces the noise greatly but the filter is very sluggish. In this work, the best value of α was found to be 0.5.

The moving average was less effective than the double exponential filter with $\alpha = 0.5$. The profile of the controlled variable was smoother but the control actions were more delayed when the moving average was used.

The digital filters were tested with two control algorithms (a self-tuning regulator and a feedforward controller). The same conclusions were obtained with both controllers, indicating that the choice of the digital filter is independent of the control strategy to be implemented.

The runs have shown how important the choice of the digital filter is to achieve a good control performance. The smoother the digital filter, the sluggisher it is. For control tasks, the digital filter to be chosen should block the noise without introducing a relevant delay in the control loop.

6. Nomenclature

J = number of past data points which are being averaged (equation 2)
n = current sampling instant
R = reflux ratio
R_{min} = minimum reflux ratio
X = measured value
$x_{D,SP}$ = set-point distillate composition, mole fraction
Y = filtered value
y_{top} = vapour composition, mole fraction
y^* = deviation variable = $y_{top} - x_{D,SP}$
α = parameter (equation 1)

References

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Seborg, D. E., T. F. Edgar and D. A. Mellichamp (1989). *Process Dynamics and Control*, John Wiley & Sons, Inc., New York, pp. 538-542.