IDENTIFICATION OF A GLASS TUBE DRAWING BENCH

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Abstract: In this paper we present a comprehensive application of identification methods for the modelling of a glass tube drawing process which is multivariable. A preliminary structure determination is carried out through a correlation analysis. Parametric models are then obtained, using a prediction error method, for different tube sizes. This identification study leads to the following non-standard conclusion : it appears to be more suitable to use different sampling periods (ranging from 1 to 5 sec.) for the different input-output relations of the multivariable model but to adopt a unique global model structure for different tube sizes provided time varying sampling periods (depending on the drawing speed) are used.

Keywords: System identification, Multirate sampling.

1. INTRODUCTION

Identification theory is now a standard course at graduate level in most engineering departments. However, its use in practice, with the aim of obtaining better models of processes which are difficult to control, does not seem to be so widespread. Particularly, process engineers show a certain reluctance to use so called "black-box" models arguing of their lack of physical signification. Therefore, it may still be useful to describe in some details an identification application, showing how it may improve the understanding of the process.

This paper is thus devoted to the description of an identification procedure applied to a glass tube drawing process. The motivation for this identification study was mainly the poor performances of the PID control loops applied to the process, even after the parameters of the controllers had been tuned several times. The fact that this process has to produce glass tubes of different calibres also increases the difficulties of a good tuning. The object of this paper is hence to apply the identification tools on a very systematic way and to try to convince the readers, and hopefully readers from the industry world, that even the use of black box models can improve the physical insight that one has in a given process.

The outline of the paper will be as follows : in section 2, we shall describe the process under study as well as the data that were available for the identification. Section 3 is devoted to a correlation analysis which has been carried out on the collected data prior to the use of parameter estimation algorithms. This correlation analysis allows to obtain some approximate values for the delays of the relations, which play an important role as can be understood from the description of the process.

The identification of parametric models is described in section 4, and because of the aim of this paper, we shall be systematic and show how we come to the "best model". Several tools (equation error standard deviation, maps of poles, correlograms of the equation errors) are used to choose the best model and this section points also out to the problem of the choice of the sampling period for the various relations.

The last section of the paper illustrates the results obtained with a different tube calibre and studies the possibility of working with a variable (drawing speed dependent) sampling period.

2. DESCRIPTION OF THE PROCESS AND OF THE DATA

The process under study is a glass tube-drawing bench, and is depicted in Figure 1. Melted glass, coming from the furnace through a feeder, flows into a bowl at the end of the feeder and drops onto a tilted rotating cylinder. The glass winds round the cylinder and slowly slides towards its end, while the glass layer is homogenizing. Air is also blown through a channel inside the cylinder.

At the end of the cylinder, the glass sleeve forms a bulb, drops and is drawn on rollers, over a distance of (around) 50 to 70 meters. The drawing bands are located at the end of this drawing line, which is also the cooling zone of the tube.

The first part of the process, up to 5 to 10 meters after the bulb, is located in a closed chamber, to prevent a too rapid cooling of the tube. The thickness and the diameter of the tube are measured with a laser beam measuring device, just outside the chamber. The diameter of the cold tube is also measured at the end of the drawing line.

These two variables, which are the outputs of the process, are controlled by means of the air blowing pressure and the drawing speed. For each of these control variables, there is a control loop between the setpoint and the actual value.

This process is mainly characterized by the four variables which have been mentioned. However, there are several perturbations acting on the process, but which are not measured, e.g. the glass temperature in the bowl which will change the glass flow, or the rotation of the cylinder which sometimes induces a cyclic perturbation.

Another important feature of this process, as will be seen later, is that, due to the location of the measuring device, there is a long transportation delay between the point where the tube dimensions are modified by means of the control variables and the point where this effect is measured.

The goal of the study was to obtain a good model of the process in order to improve the control of the diameter and thickness of the tube, which are presently controlled by means of two PID controllers, one linking diameter and pressure, the other thickness and speed.

For the purpose of this identification study, several experiments were made with PRBS sequences applied to the setpoints either of the pressure or of the speed, the other setpoint being kept constant. An attempt to apply PRBS sequences to both inputs at the same time failed. Indeed, perturbations applied simultaneously on both inputs of the process made the glass tube break. Hence, due to the nature of these experiments, it has not been possible to identify directly multi-input multi-output models. In the sequel, we will thus study separately four different relations, each linking one of the inputs to one of the outputs.

Up to 5000 samples, with a sampling period of 0.5 second, were taken. These samples were filtered later on, in order to produce data sampled at 1 second, which seems more appropriate compared to the delays and time responses of the process. Most of the experiments were carried out for a particular size of the tube (called calibre 25) : diameter 15.6 mm and thickness 0.53 mm, which correspond to mean values for the speed equal 121.7 m/min and for the pressure equal to 45.74 mm C.E.

However, a few other experiments were performed on a tube of much greater size (calibre 80, diameter = 22.3 mm, thickness = 1.2 mm) which corresponds to a drawing speed three times smaller (drawing speed = 39.15 m/min, pressure = 48.98 mm C.E.). These data records were then also filtered to produce records with a 3 second sampling period. The reason for this was that we hoped, with this variable sampling period, to obtain the same model for different tube sizes. A sample of the collected data is illustrated in Figure 2.

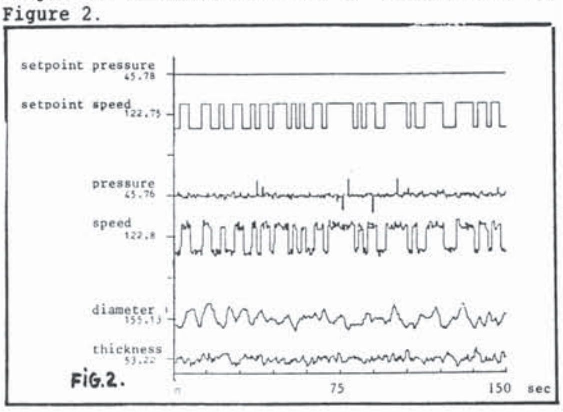

FIG.2.

This figure shows that the local control loop for the speed is much better than the control loop for the pressure. In the following identification study, we have chosen to identify the relation between the actual values (and not the setpoints) of the speed and the pressure as inputs and diameter and thickness as outputs. The local control loops will therefore not be included in our model. This means that the order of the transfer functions will be kept small, but also that, if these models are to be used in a control algorithm, then the pressure control loop should be improved in order to reduce the difference between setpoint and actual value.

3. CORRELATION ANALYSIS

The first treatment which has been applied to the data is a correlation analysis. This correlation is estimated by the following formula :

$$\rho_{yu}(k) = \frac{1}{\sigma_y \sigma_u}\left[\frac{1}{N}\sum_{i=k}^{N} y(i)\, u(i-k)\right]$$

The aim of those correlations computations is to get some preliminary information about the input-output relation and particularly about the dead times, which play an important role in this study. Figure 3 illustrates the cross correlations for the four input-output relations on the calibre 25 tube.

The main conclusions which can be drawn from this figure are that there is no significant relation between pressure and thickness and that the approximate values of the dead times for the three other relations are respectively 11 seconds for the speed-thickness relation, 4 seconds for the speed-diameter relation, and 7 seconds for the pressure-diameter relation. The same correlation analysis has been performed on the data corresponding to the second calibre. The approximate values of the dead times are shown in Table 1, and compared to the dead times of the first calibre.

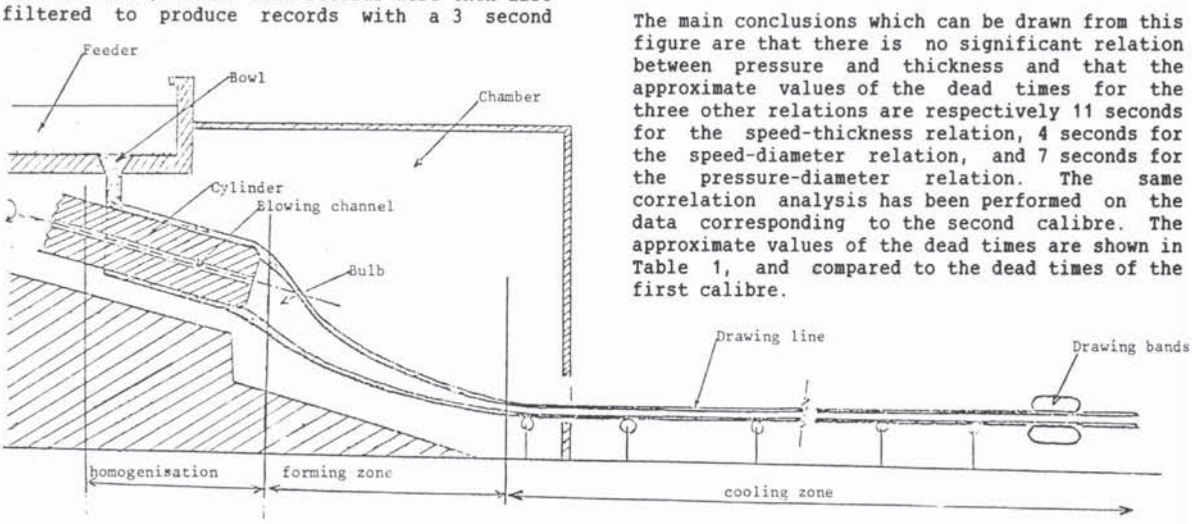

FIG.1. The glass tube drawing bench.

		Calibre 25	Calibre 80
Mean speed		121.8 m/min	39.15 m/min
Speed-thickness	Time delay	11 sec	35 sec
	Space delay	22 m	22 m
Speed-diameter	Time delay	4 sec	14 sec
	Space delay	8 m	9 m
Pressure-diameter	Time delay	7 sec	22 sec
	Space delay	14 m	14 m

Table 1. Dead times suggested by the correlation analysis

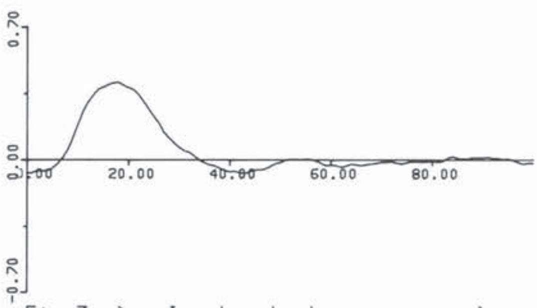

Fig 3 a) : Input-output cross correlations for the calibre 25 tube (pressure/diameter relation)

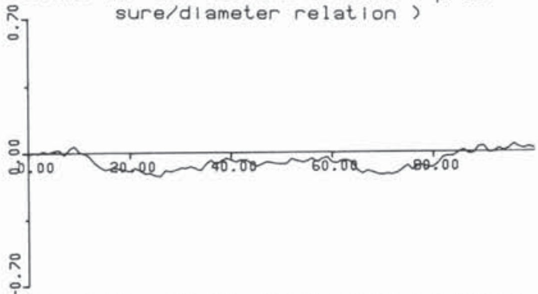

Fig 3 b) : Input-output cross correlations for the calibre 25 tube (pressure/thickness relation)

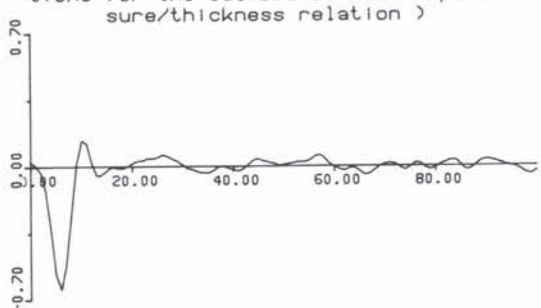

Fig 3 c) : Input-output cross correlations for the calibre 25 tube (speed/diameter relation)

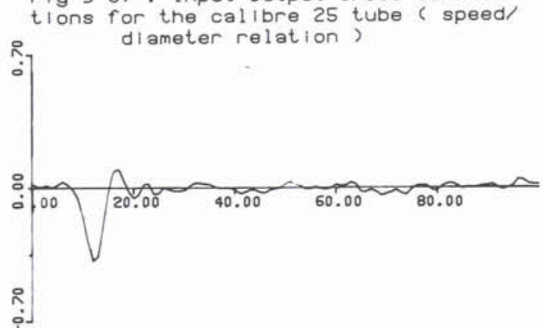

Fig 3 d) : Input-output cross correlations for the calibre 25 tube (speed/thickness relation)

This table clearly shows that the delay, expressed in meters, is constant when the calibre varies. This is consistent with the description of the process which indicates the presence of a transportation delay. Investigations will be made later on (see section 5) in order to test whether other characteristics of the transfer functions (poles, settling time, ...) can be made independent of the tube size.

4. IDENTIFICATION OF PARAMETRIC MODELS

In this section, we shall describe the identification of LS models from the input-output data presented in section 2. A LS (least squares) model is of the form :

$$y(k) = -\sum_{i=1}^{n} a_i\, y(k-i) + \sum_{i=1}^{m} b_i\, u(k-i-\tau) + e(k,\theta)$$

In this expression :

- $y(k-i)$ and $u(k-i)$ denote data (output and input respectively),
- n is the autoregressive order,
- m is the input moving average order,
- τ is the dead time (pure delay, $\tau \geq 0$),
- $\theta = (a_1,\ldots,a_n,b_1,\ldots,b_m)$ is the parameter vector,
- $e(k,\theta)$ is the equation error whose value obviously depends on the parameter values.

The model structure is defined as the triple (n,m,τ).

For a specific structure, the "best" model in a LS sense is given by the parameter vector θ which minimizes the following LS criterion :

$$J(\theta) = \frac{1}{N-\mu} \sum_{k=\mu}^{N} e^2(k,\theta)$$

$$\hat{\theta} = \arg\min_{\theta} \left[J(\theta) \right]$$

where N is the length of the input-output data sequence and $\mu = \max\,(n,\, m+\tau)$.

The identification problem is then the problem of finding a good structure for the process under consideration from one (or several) data sequences.

To solve this problem, various structures (i.e. various combinations of the orders n and m, and of the dead time τ) are tried : for each of them the "best" LS model is computed.

Our approach for selecting a good structure, among the candidate structures, is then based on a careful and exhaustive examination of the following features of each of these LS models :

1) The sample equation error variance :

   $\sigma^2(id) = J(\hat{\theta})$

2) The correlogram of the equation error sequence,
3) The map of the poles of the model,
4) A "validation" error variance obtained by applying the model to an alternative data sequence. This variance is denoted : $\sigma^2(val)$

Speed-Diameter

The first relation which is examined is that relating the diameter variations to the drawing speed. For this relation a set of 2700 data were available, with a sampling period of 1 second. This set of data has been divided into two subsets : the first, with 1500 samples, has been used for the LS models estimation and the second, with 1200 samples has been used for the validation.

We have identified structures with an increasing number of parameters and with values of the dead time around 4 seconds, which was indicated by the correlation analysis.

In figure 4, the identification and validation variances are plotted for increasing value of dim θ. For each value of the dimension of θ, the best LS structure has been used and is indicated on the figure.

From this figure, it appears immediately that the best model is that corresponding to the structure (2,3,4). The decreases of $\sigma^2(id)$ and $\sigma^2(val)$ are significant up to dim θ = 5. Afterwards, both values remain constant and a third order model is certainly not indicated in this case. The poles and zeros are illustrated in Figure 5 and Figure 6 gives the step response of the model, showing a settling time of approximately 6 seconds, which is consistent with the use of a 1 second sampling period.

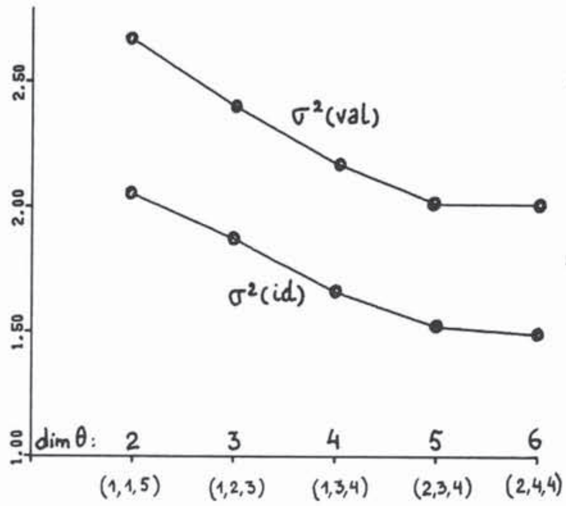

Fig 4 : Estimation and validation variances versus dim θ for the speed/diameter model

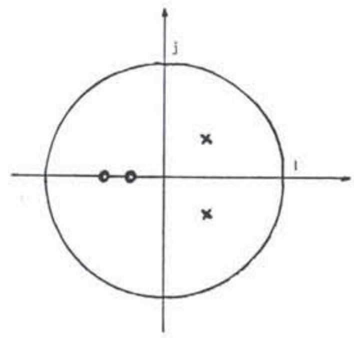

Fig 5 : Pole-zero configuration of the best speed/diameter model

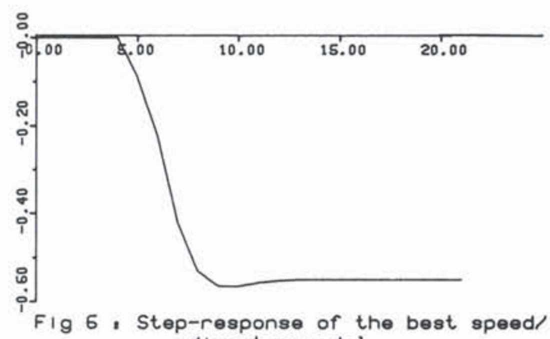

Fig 6 : Step-response of the best speed/diameter model

Pressure-Diameter

We shall now try to identify a model for the pressure-diameter relationship with the same sampling period (Te = 1 sec.) as above.

In this application, we use a set of 1000 data for the LS model estimation and a set of 800 data for the validation.

All the structures with dim $\theta = n + m \leqslant 10$ and $8 \leqslant \tau \leqslant 12$ have been tried.

Table 2 shows the best models, according to the $\sigma^2(id)$ criterion obtained for each value of dim θ.

In Figure 7 we give the poles maps of a set of "all poles" models with autoregressive orders ranging from 1 to 4 (Table 3).

The results of Table 2 are clearly in favour of either a model of order n = 1 or a model of order n = 3 with a dead time = 11 sec. (wich is larger than the value suggested by the correlation analysis).

The main relative decrease of $\sigma^2(id)$ or $\sigma^2(val)$ is indeed obtained when passing from n = 1 to n = 3 (the case n = 2 being not accepted by the table).

This first indication is strenghtened by Table 3 and Figure 7. The four models of this table have a dominant real pole close to the unit circle and corresponding to a time constant of approximately 18 sec. With the second order model we add a second negligible pole to the first one : this explains why the performance is not increased.

With the third order model, we add 2 complex conjugate poles, giving a performance improvement which appears to be more significant. Finally, with a fourth order model we add again a negligible pole.

In fact, all the models we have tried exhibit a largely dominant time constant of 18 sec. and behave essentially as first order systems.

Hence, from a parameter parsimony viewpoint and in view of the correlograms of Figure 8, it seems reasonable to adopt a first order model or, at most, a third order one.

dim θ	n	m	τ	σ_{id}^2	σ_{val}^2
2	1	1	11	1.374	1.729
3	1	2	11	1.357	1.727
4	3	1	11	1.302	1.633
5	3	2	11	1.275	1.620
6	3	3	11	1.257	1.598
7	3	4	11	1.237	1.587
8	3	5	10	1.212	1.524
9	4	5	10	1.201	1.485
10	5	5	10	1.191	1.475

Table 2 : Parameter estimation and validation results for the pressure-diameter relation (Te = 1 sec.)

n	m	τ	σ_{id}^2	b_1	a_1	a_2	a_3	a_4
1	1	11	1.374	0.123	0.930			
2	1	11	1.371	0.125	0.910	0.021		
3	1	11	1.301	0.141	0.901	-0.188	0.221	
4	1	11	1.300	0.144	0.902	-0.183	0.195	0.028

Table 3. Parameter estimation results for a set of all poles pressure-diameter models (T_e= 1sec).

However, by contrast with the results of the speed-diameter identification, we must recognize that the conclusion is not completely clear since Table 2 shows a steady and persistent decrease of both estimation and validation variances until dim θ = 10 (and actually even much further). The reason is that the sampling period of 1 second is, in this case, very small compared to the settling time (≈ 50 sec.) of the process (as it is confirmed by the location of the dominant pole close to the unit circle).

Hence, from a control design viewpoint, it seems more pertinent to work with a larger sampling period, say 5 sec., for the pressure-diameter relation than for the other relations.

Figure 9 summarize the identification results obtained from the set of the 360 available data with a sampling period Te = 5 sec. We see from this figure that the conclusion is much more clear. The best parameter dimension is at most dim θ = 5. In fact, we have decided to adopt the best structure with dim θ = 4, namely the structure (1,3,2) which gives a nearly optimal error variance (see Fig. 9) together with a very "white" error correlogram (Fig. 10). Notice also that this selected model is of order 1, which is consistent with our previous results for this relation.

Speed-Thickness

A similar study has been performed to identify the speed-thickness relation from a set of 2700 data, with a sampling period of 1 sec. A model with structure (3,4,11) has been selected. Its settling time is of approximately 5 seconds, which is consistent with the sampling period.

Conclusion

Thus, the best model we have selected for the global multivariable glass drawing process is as shown in Figure 11.

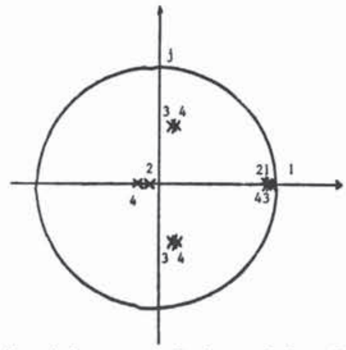

Fig 7 : Poles map of the models of Table 3 (the numbers refer to n)

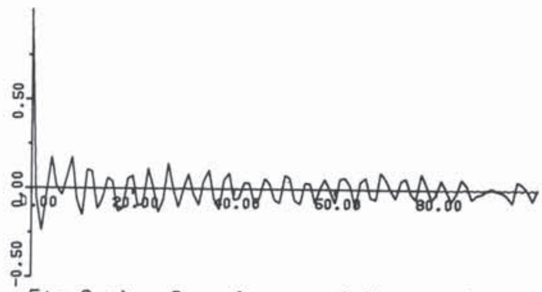

Fig 8 a) : Correlogram of the equation error autocorrelation of the (1,1,11) model in Table 2

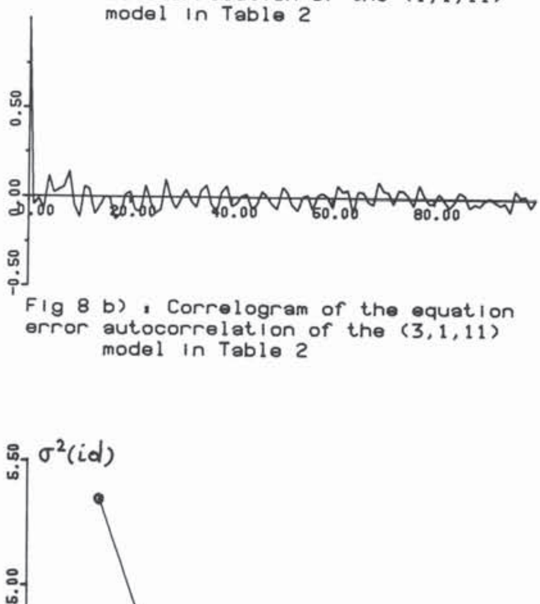

Fig 8 b) : Correlogram of the equation error autocorrelation of the (3,1,11) model in Table 2

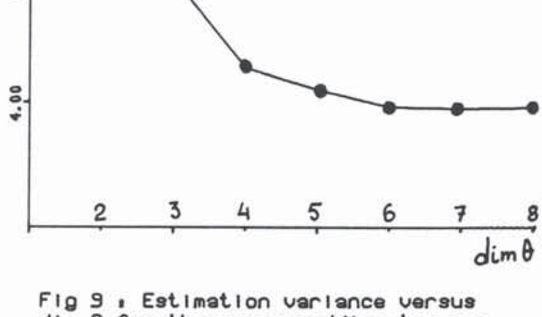

Fig 9 : Estimation variance versus dim θ for the pressure/diameter relation (Te = 5 sec)

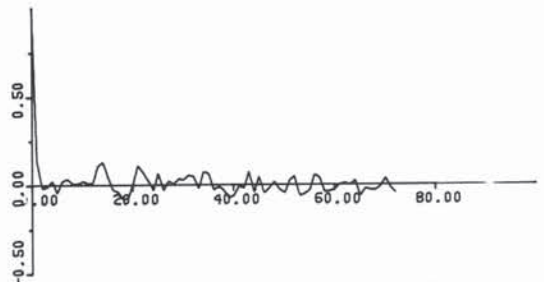

Fig 10 : Correlogram of the best pressure/diameter model (1,3,2) with a sampling period Te = 5 sec

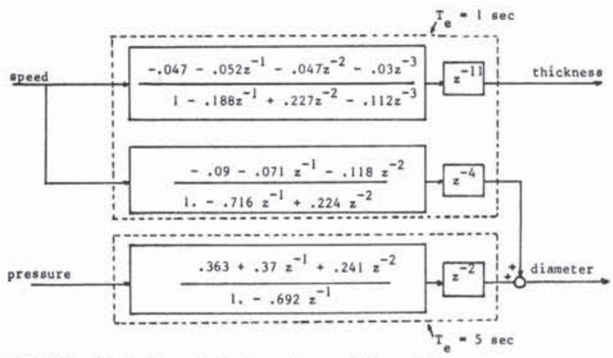

FIG.11. Global model for the calibre 25.

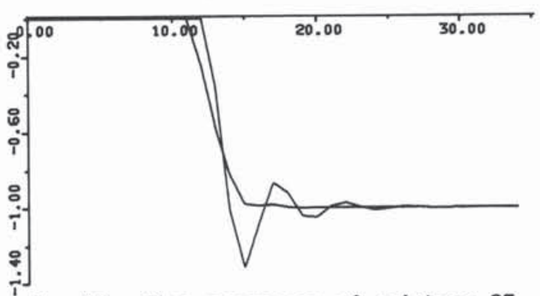

Fig 12 : Step-responses of calibres 25 and 80 models with a normalized time scale (speed/thickness relation)

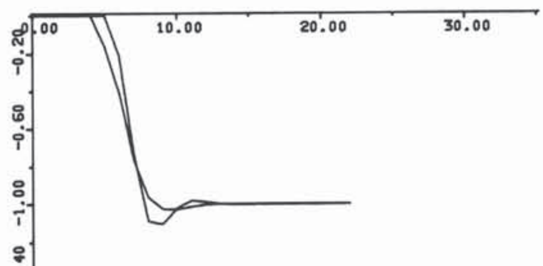

Fig 13 : Step-responses of calibres 25 and 80 models with a normalized time scale (speed/diameter relation)

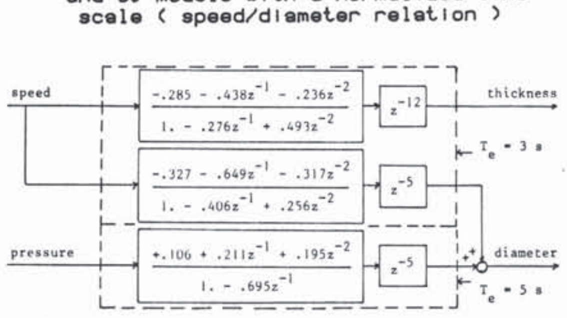

Fig 14 : Global model for the calibre 80

5. IDENTIFICATION OF THE CALIBRE 80 TUBE

Other identification experiments have been carried out with the second tube size for which data have been collected. A first conclusion which has already been drawn from the correlation analysis in section 3 is that the space delays are constant. This means that if the sampling period is inversely proportional to the mean drawing speed (for example 1 second for the calibre 25 with a mean drawing speed of 120 m/min and 3 seconds for the calibre 80 with a mean drawing speed of 40 m/min), then the delays of the three relations expressed in sampling period units are constant.

From this first observation one can also make the hypothesis that, by modifying the sampling period as explained above, one could obtain models with a similar dynamical behaviour for each of the three input-output relations at various calibres.

This hypothesis appeared to be exact for the two models with the speed as input. The best models obtained for the calibre 80 with a sampling period of 3 seconds and after a careful identification study are presented on fig. 14 and their step responses, compared with those of calibre 25, are shown on fig. 12 and 13 with normalized static gains. It is clearly seen that the delays, the settling times and the structures are very similar, provided the sampling period is normalized with respect to the drawing speed.

From a control design viewpoint, this means that one could think to adopt a nominal "mean" model which would be used, for instance, to initialize the self tuning of the controller at each change of calibre, in order to ensure a "bumpless" transfer from one calibre to another.

On the other hand, the identification of the pressure-diameter relation does not lead to the same conclusion. The settling time is approximately independent of the calibre of the tube. In this case, it seems therefore more convenient to adopt a unique nominal model with a constant sampling period of 5 seconds but with variable delays, depending on the drawing speed, for the different calibres.

6. CONCLUSION

We have presented in this paper a comprehensive application of identification methods to a multivariable industrial process. The best models have been selected mainly through a careful inspection of the behaviour of the equation error variances and of the validation variances. The first conclusion which can be drawn from this identification study is that it is necessary to use different sampling periods for the relations involving the speed and for the relation with the pressure as input. This will of course make the control design more complex.

A second observation is that the models of the two relations with the speed as input can be made approximately independent of the tube calibres provided a variable sampling period is chosen (inversely proportional to the mean drawing speed). The pressure-diameter relation however seems to have a constant dynamics for the various calibres.

This paper has also shown how standard identification tools can help a process engineer in the understanding of a complex process.