Advanced Control Strategy for A Digital Mass Flow Controller

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Abstract

Mass Flow Controllers are complex mechatronic devices the design of which involves many techniques and skills in various scientific domains. Due to the slow response time of the sensors embedded in such devices, it is critically important to control gas flow variations in processes used in semiconductor industry. This paper shows how a digital controller for MFCs can be mathematically computed once the dynamic characteristics of the open-loop system have been identified. The proposed control method goes beyond prior art control methods as it explicitly takes into account the dynamics of the sensor, computes the digital controller appropriate to the order of the open-loop model and imposes a desired closed-loop transient response. The simulations performed and experimental results obtained with this new type of digital controller were very promising.

Keywords: Control engineering, Fluid flow control, Digital filters, Mechatronic device.

1. Introduction

For many years, Mass Flow Controllers (MFCs) have been the most effective means of precisely controlling gas flow in processes used in semiconductor industry. MFCs are complex mechatronic devices the design of which involves many techniques and skills in various scientific domains such as fluid dynamics, mechanical engineering, thermal engineering, electronics and more recently computer science. Many environmental and installation factors influence the operational behaviour of MFCs which are considered to be critical equipments in the semiconductor manufacturing process [1]. Indeed, malfunctions of MFCs have significant effects on yield, downtime and mean time to repair. That is the reason for the considerable effort devoted by MFC constructors to research and development aimed at improving their characteristics. With digital technology, MFCs entered a new era. Digital technology provides greater flexibility, better calibration and control functionality, better communication, better monitoring and better performance optimization [2][3]. In this paper we show how digital technology can help improve the control of MFCs by taking into account the dynamic characteristics of such complex devices.

We propose a new strategy for controlling a digital MFC. It exploits a linear model of the open - loop device and mathematically calculates the digital controller which imposes the desired transient response to the MFC in closed-loop operation. In the case considered below, the main difficulty is how to deal with a sensor that is slow by comparison with the variations in flow rate of the gas circulating through the device.

Section 2 describes the physical principle and the structure of the MFC concerned. Section 3 discusses two main control strategies. In the first, the real gas flow rate is estimated inside the loop before being used by the controller. Such a strategy increases the noise/signal ratio and may decrease the stability margin of the device. In the second strategy, the controller directly exploits the signal provided by the sensor, without needing to estimate the real flow rate. In section 4 the two strategies are compared by means of simulations. Section 5 presents experimental results for an adaptation of the proposed method to a real case validated by the MFC production department.

2. Operation of MFCs

2.1. Principles of MFCs

MFCs are used wherever accurate and precise measurement and control of a mass flow of gas is required independent of flow pressure change and temperature change within a given range. As shown in Fig. 1, a MFC can be separated into four main components: a bypass, a sensor, an electronic board and a regulating valve. The flow is divided between a capillary tube, where the mass flow is actually measured, and a flow restrictor or bypass, through which most of the flow passes. Because the sensor element can only measures low flow rates (typically

5 sccm[1]), the bypass is designed in such a way that the flow through the sensor and the flow through the bypass are always proportional to the flow range for which the MFC is built. A study of such thermal mass flow meters can be found in [4]. The electronic board amplifies and linearizes the sensor signal. The output of the electronic board gives a signal proportional to the total flow circulating in the device [5].

The sensor uses the thermal properties of the gas to measure the mass flow rate assuming (ideal) insensibility of the properties to temperature variations of the gas and essentially constant pressure. In the MFCs considered below, two heated resistance thermometers are wound round the capillary tube as shown in Fig. 2. The gas flowing inside the tube creates a temperature gradient inside the tube. At zero flow, the upstream and downstream temperatures are equal. For flow under 5 sccm, the first wound resistance is at a lower temperature than the second one and the temperature difference is proportional to the flow. The coils of the resistance are made from heat-sensitive wire so that the temperature differences due to the flow are directly converted into resistance changes. These resistance changes are converted into a voltage by a Wheatstone bridge. Such a thermal type of sensor presents the main advantages to be precise, robust and not incursive (some of the gases used in semiconductor industry are so much corrosive that they should damage any current incursive sensor).

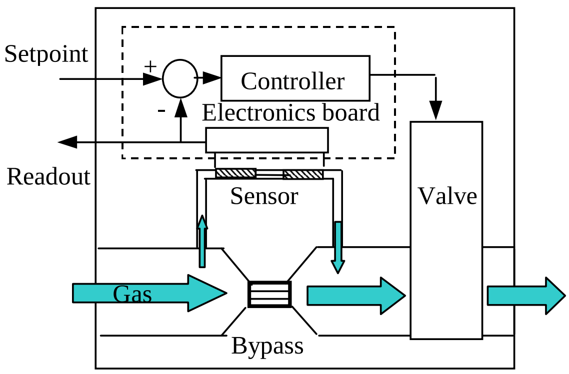

Fig. 1. Diagram of the mass flow controller.

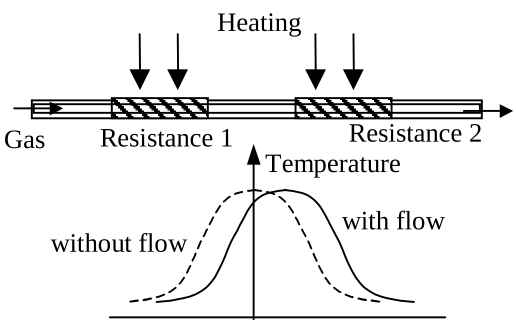

Fig. 2. Sensor temperature profile in the capillary tube.

[1] sccm: standard cubic centimeters per minute

Various valve technologies can be used (thermal, magnetic, and piezoelectric). The valves under consideration are actuated by a magnetic solenoid.
The electronic board compares the amplified mass flow rate value to the desired setpoint. This comparison generates an error signal that is used by the electronic controller to control the valve that will open or close until the output is equal to the setpoint.
The most popular controller is the Proportional Integral Derivative controller (PID) which can be easily manually tuned but whose performances are rather limited when the system under control presents pure delay or high order dynamics. As customers' requirements concerning MFC performance become more demanding, the complexity of the MFCs' dynamic behaviour needs to be better understood and higher performance digital controllers need to be designed. Section 3 presents and discusses control strategies.

2.2. Dynamic characteristics of a MFC.

According to technological choices and flow ranges, MFCs may present different dynamic characteristics. Open-loop analysis of an MFC reveals that such a device is a non-linear system, whose steady gain and response time vary with flow rate. However, to a first approximation the system can be considered as linear. This assumption is quite acceptable for small variations around fixed flow rates.
According to the desired accuracy of the modeling procedure, the order of the linear model describing the MFCs can vary between one and three.
The response time of the valve (time constant denoted as τ_0) is generally short compared to the sensor response time. The dominant transient response is due to the thermal sensor which can be simply described as a first order or as a second order system.

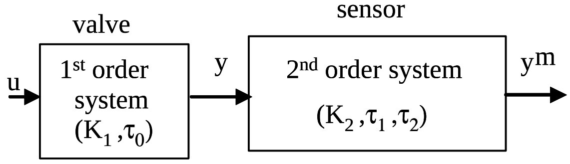

Fig. 3. Open-loop model of the device: K_1, K_2 are steady gains; τ_0, τ_1, τ_2 are time constants.

It must be emphasized that the effective flow rate presents the same dynamic behavior as the voltage applied to the valve (when the time constant of the valve can be neglected). This has been experimentally verified using a very fast mass flow meter based on measurement of differential pressure. So the main response time limitation comes from the sensor.
If u designates the voltage applied to the valve, y the voltage corresponding to the real flow rate and y^m the voltage delivered by the sensor, the model

developed can be represented as a third-order system as shown in Fig. 3.

3. Control strategies

3.1. Issues concerning MFC control.

The main difficulty to solve when controlling an MFC is to deal with a sensor which is very slow as compared to the flow rate variations of the gas circulating through the device.
The following section will compare two control strategies. The first is illustrated in Fig. 4 and consists in estimating y^e, the real gas flow rate within the mass flow, from the signal y^m delivered by the sensor. The difference between the setpoint value y^c and the estimated flow rate y^e is then delivered to the controller that pilots the valve. The main drawbacks of such an approach are:
- The estimation of the real flow rate is based on computing successive derivatives, which decreases signal noise ratio.
- The method is not robust, as flow rate estimation errors may generate dramatic overshoots in the transient response of the device.
- The computation time necessary to estimate the flow rate introduces a delay in the loop and decreases the stability margin.

As shown in Fig. 5, the second strategy does not present the drawbacks of the former approach since the flow rate estimation module is removed from the control loop. This module provides the users with the real flow rate data. Such a strategy consists in directly exploiting the signal provided by the sensor, without first estimating the real flow rate.
The main drawback of this approach is that it requires more mathematical development and is less intuitive than the former strategy.
To be efficient, both the two approaches require precise knowledge of the sensor model.

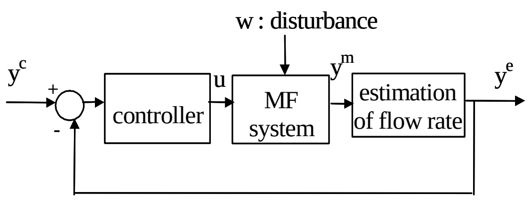

Fig. 4. Control scheme based on the estimated flow rate.

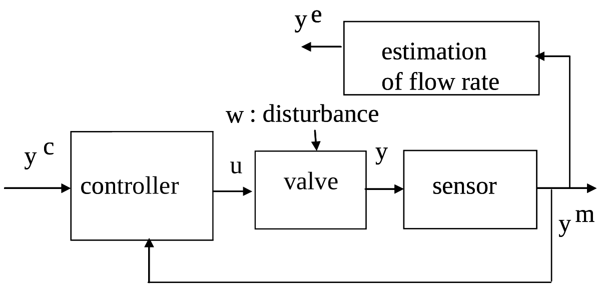

Fig. 5. Control scheme based on the measured flow rate.

Sections 3.2 and 3.3 presents and discusses the two control strategies.

3.2 Control based on the estimated flow rate.

Estimating the real flow rate from the sensor response: It is generally assumed that the real flow rate is proportional to the voltage applied to the valve. Let us consider the second order dynamic model of the open-loop system: the transfer function between y^m and u can be written as:

$$\frac{Y^m(s)}{U(s)} = \left[\frac{k_0}{(1+\tau_1 s)} + \frac{k_1}{(1+\tau_2 .s)}\right] \quad (1)$$

with $k_0 + k_1 = K_1.K_2 = K$, and s is the Laplace variable.
The unit step response is then:

$$y^m(t) = K - k_0 \exp(-t/\tau_0) - k_1 \exp(-t/\tau 1) \quad (2)$$

So the following estimation y^e of the real flow rate can be calculated as proposed by Vyers [6]:

$$y^e(t) = y^m(t) + \alpha dy^m(t)\big/dt + \beta d^2 y^m(t)\big/dt^2 \quad (3)$$

With (α, β) solution to:

$$\begin{bmatrix} 1/\tau_1 & -1/\tau_1^2 \\ 1/\tau_2 & -1/\tau_2^2 \end{bmatrix} . \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad (4),$$

From (4), we obtain: $\alpha = \tau_1 + \tau_2$ and $\beta = \tau_1 \tau_2$.
Such an estimation method is an improvement upon prior art transient compensation methods which only considered the first derivative term.
The calculation of the flow rate can be easily digitally implemented. Let us consider a function f(t) and the sampling period Te, then the first order derivative f' and the second order derivative f" can be calculated at time k.Te as :

$$f'(kT_e) = f'_k = (f_k - f_{k-N})/NT_e \text{ with } N \geq 1$$
$$f''(kT_e) = f''_k = (f'_k - f'_{k-M})/MT_e \text{ with } M \geq 1$$

Where f_k and f_{k-N} are respectively the k^th and (k-N)^th delay values of f(t) respectively.
Introducing such a discretization technique in expression (3), we obtain:

$$y_k^e = y_k^m + (\alpha/NT_e)(y_k^m - y_{k-N}^m) + (\beta/MNT_e^2)(y_k^m - y_{k-N}^m - y_{k-M}^m + y_{k-M+N)}^m) \quad (5)$$

Controlling the flow rate through the MFC: As shown in Fig. 4, the estimated flow rate y^e is then compared to the setpoint y^c to generate an error signal. The digital error is generally delivered to a Proportional Integral Controller (performed digitally if the MFC is digital) [6]. An integral term is necessary to cancel steady state error and compensate constant disturbance.

Discussion: Although the method has given satisfactory results, it suffers from several drawbacks:

- From a mathematical point of view, the mass flow estimation method (3) is not correct insofar as the variations of the u and y signals can not be assimilated to step variations. Indeed, aside from the step response, other terms taking into account the dynamics of the input should be considered.
- In practice, the noise is amplified by the derivative operations and it may be necessary to filter such noise generated on the derivative signal [6].

3.3. Control based on the measured flow rate

RST control theory:. Grouping together the open loop system, including the valve, sensor and A/D D/A converters, in the same block, the control loop of Fig. 5 can be redrawn as in Fig. 6. Disturbance w (typically constant gas pressure variation) is assumed to act as an additive signal on the sensor signal y^m.

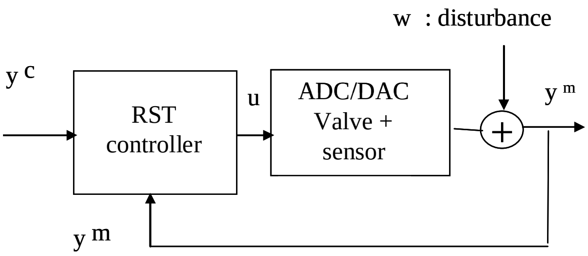

Fig. 6. RST control architecture.

In the RST control structure shown in Fig. 7, B/A is the z-transfert function of the open loop system. R, S, T are polynomials that constitute the digital controller whose coefficients have to be calculated. Using the z-transform, polynomials A and B are calculated from the continuous open loop model:

$$A(z^{-1}) = 1 + a_1.z^{-1} + a_2.z^{-2} + ...$$

$$B(z^{-1}) = z^{-d}.(b_1.z^{-1} + b_2.z^{-2} + ...) \ ,$$

where d is an integer representing any pure delay in the system. The remaining polynomials R, S and T have to be computed as:

$$R = r_0 + r_1.z^{-1} + r_2.z^{-2} + ...$$

$$S = s_0 + s_1.z^{-1} + s_2.z^{-2} + ...$$

$$T = t_0 + t_1.z^{-1} + t_2.z^{-2} + ...$$

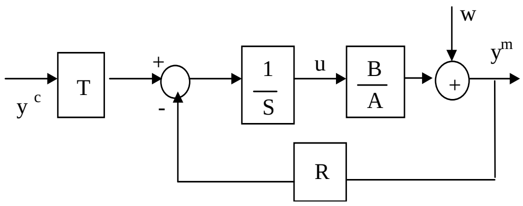

Fig. 7. RST control architecture.

At time k.Te, the command value applied to the valve is therefore:

$$u_k = \frac{1}{s_0}(t_0.y_k^c + t1.y_{k-1}^c + t_2.y_{k-2}^c + \\ ... - r_0.y_k - r_1.y_{k-1} - ... \\ - s_1.u_{k-1} - s_2.u_{k-2} - ...) \qquad (6)$$

From Fig. 7, it can be established that:

$$Y^m(z) = \frac{TB}{AS + BR}.Y^c(z) + \frac{SA}{AS + BR}.W(z) \qquad (7)$$

From expression (7) it can be deduced that in closed loop operation:

- The transient response is defined by the roots of the characteristic polynomial AS+BR.
- Any constant disturbance w can be completely compensated when S contains the factorized term $(1 - z^{-1})$.
- To cancel the steady state error, the steady state gain between y^c and y^m must be equal to one.

We thus obtain the solution $T = R(1) = R(z^{-1} = 1)$.

So the digital controller is completely defined if R and S are polynomial solutions of the Diophantine equation [7]:

$$P° = AS + BR \qquad (8)$$

where P° is the desired characteristic polynomial. According to the specified closed loop transient response, P° should be a one-degree or two-degree polynomial depending on whether the device has to behave as a first order system or a second order system in closed-loop operation.

Calculating R, S and T in the case of the MFC: Assuming that the flow rate is proportional to the valve voltage, it is sufficient to impose the dynamics of the u signal in order to impose the transient flow rate response.

The z-transfer function between u and y^c is:

$$\frac{U(z)}{Y^c(z)} = \frac{A.T}{A.S + B.R}$$

The dynamics of signal u are determined by the roots of the characteristic polynomial $[AS + BR]$ but also by the roots of polynomial A which can have a considerable influence on the overshoot.

In order to prevent any overshoot, the roots of A have to be cancelled by some roots of the characteristic polynomial (in theory this is possible only if the root modules are smaller than one).

So, S and R should be polynomial solutions of the modified Diophantine equation:

$$AS + BR = P°A \qquad (9)$$

With $S = (1 - z^{-1})S_1$ and $R = A.R_1$ where S_1 and R_1 are polynomials to be calculated.

So eliminating A in (9), R_1 and S_1 must be polynomials solution of the Diophantine equation:

$$(1 - z^{-1})S_1 + BR_1 = P° \qquad (10)$$

Solving such a Diophantine equation consists in making the left and right polynomials of the equation equal. The unknown R_1 and S_1 coefficients are then solutions of a linear system of equations.

Fig. 8 illustrates the effect of polynomial A compensation method in the case of a first order open-loop model of the MFC. When the RST controller is computed from expression (8) to impose fast, precise and without overshoot step response of the sensor signal $y_A{}^m$, real flow rate y_A presents unacceptable overshoots. When the RST controller is computed according to polynomial A compensation method (10), the real flow rate y does not present any overshoot and follows the specifications defined by the characteristic polynomial P^0. The sensor signal y^m is slower than the real flow rate y.

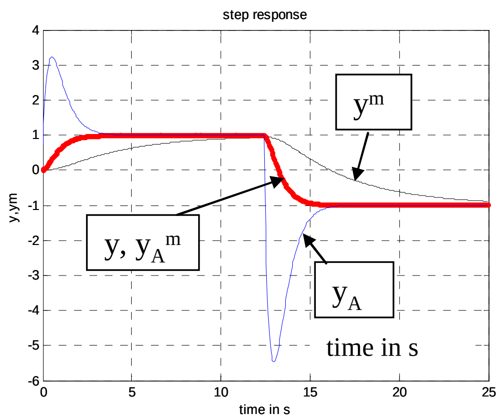

Fig. 8. Effect of polynomial A compensation.
K1*K2=0.07, τ_0 = 0s, τ_1 =4s, τ_2 =0s.

Without compensation: $y_A{}^m, y_A$.

With compensation: y^m, y.

Discussion: Using the method presented above, the digital controller can be calculated exactly provided the open-loop system model is identified.
- The controller is calculated in order to impose the desired transient response for the closed-loop system.
- There is no pure derivative computation so the noise amplification effect is limited.
- The synthesis of the controller is independent of the order of the model and of the desired transient closed-loop response. The higher the order of the model, the higher the degrees of polynomial R and S.

However the proposed method cannot compensate for the technological limitations of the device or for modelling approximations. In practice, if the sensor is too slow (for instance ten times slower than the closed-loop device) or if the model is not precise enough, the system becomes very sensitive to the control parameter values. In such a case, a low response time for the closed-loop system has to be chosen.

4. Simulation results

4.1 Open loop system model.

The MFC considered hereafter, is equipped with a magnetic valve and with a thermal sensor the principle of which has been described in section 2. The mass flow range is typically 2slpm [2], the gas used is oxygen with a typical inlet pressure of 2 bars.
An accurate modeling procedure of the considered device shows that the dynamical response of the sensor is the sum of two first order systems, one with a steady gain γ (0.8< γ <1) and a time constant τ_1, and another one with a steady gain (1- γ) and a time constant τ_2 (τ_2 >> τ_1). The model of the device is given in Fig. 9.

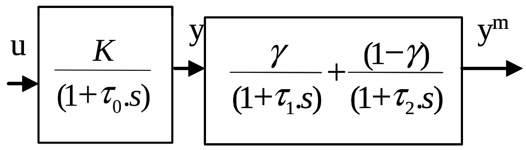

Fig. 9. Transfer function of the device in open loop configuration

The transfer function can be written as:

$$\frac{Y^m(s)}{U(s)} = \left[\frac{K}{(1+\tau_0.s)}\right]\left[\frac{\gamma}{(1+\tau_1.s)} + \frac{(1-\gamma)}{(1+\tau_2.s)}\right]$$

To a first approximation the model of the MFC can be chosen as a first order system with τ_0 = 0 and γ = 1.
A more accurate model is a second order model with τ_0 = 0 and 0.8 < γ <1.
The most accurate linear model considered is a third-order model with: $0 < \tau_0 << \tau_1 << \tau_2$ and 0.8< γ <1.
The simulation results of section 4.2 (Closed-loop step response: 0-50%, 50%-70%, 70%-40% variations of the full scale) have been obtained using the following data: τ_0 =0.1s, τ_1 = 4.0 s, τ_2 = 20.0 s, K= 0.007, γ =0.9, N=M=1. The sampling period is Te=0.05s.

4.2 Simulation results

Using the third-order model, we simulated and compared the two control strategies.

Control scheme based on the estimated flow rate: In the simulation presented in Fig 10, it can be seen that the control strategy based on the estimated flow rate and a PI controller succeeds in compensating for the slowness of the sensor (signal y^m) and to track the setpoint variations.

[2] slpm : standard liter per minute

However as discussed in section 3.2, the noise level is amplified due to the derivative terms used to estimate the flow rate according to expression (5). The steady state error between the setpoint and the real flow y is cancelled out only after the τ_2 time constant influence becomes small enough.

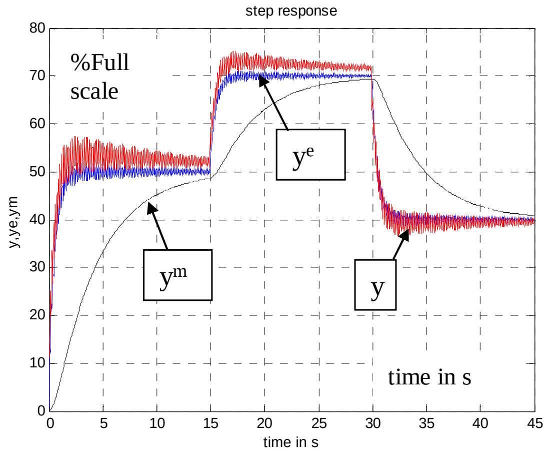

Fig. 10: Step response: y real flow, y^e estimated flow, y^m measured flow with PI controller.

Control scheme based on the measured flow rate: In the simulation presented in Fig. 11, it can be seen that the control strategy based on the measured flow rate and an RST controller succeeds in compensating the slowness of the sensor (signal y^m) and in precisely tracking the set point variations. The control law takes into account the third-order model and does not increase the noise level. The response time is defined by the characteristic polynomial P°. It can be decreased but is limited in practice by the risk of saturation of the command. In the case under consideration, and according to expression (9), R and S are third-order polynomials. Due to the degrees of R and S, it must be emphasized that there is no PID controller equivalent to such an RST controller.

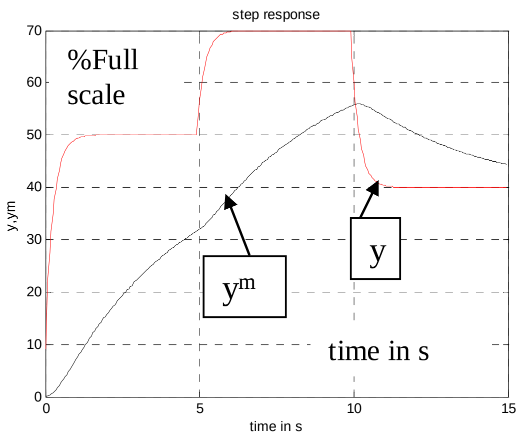

Fig. 11: Step response: y real flow, y^m measured flow, RST controller.

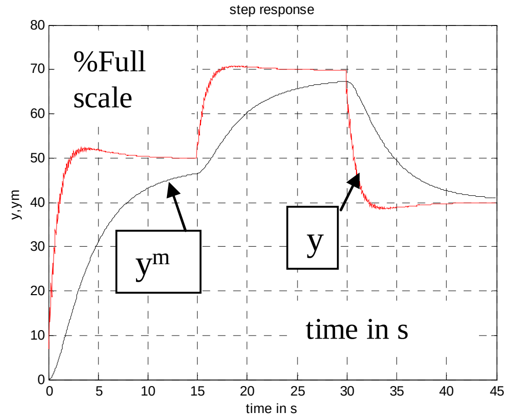

Fig. 12: Robustness test, on step response: y real flow, y^m measured flow τ_1^e = 4.1 s, τ_2^e = 22.0 s, K= 0.007, RST controller.

The proposed RST control scheme performs quite well as far as the third-order model is precise enough. The robustness test presented In Fig. 12 shows that even small errors in the estimation of time constants τ_1 and τ_2 (estimated respectively as τ_1^e and τ_2^e respectively) can create overshoots and increase the settling time.

As it is not an easy task to estimate precisely the parameters of the third order model with less than 10% relative error, (particularly for parameters τ_2 and γ), section 5 presents the solution that has been proposed to improve the behaviour of the real device.

5. Experimental results

As we have already pointed out, excessive sensor response time and modelling error may have significant effects on the performance of the MFC as defined by standard SEMI E17-00-0600.
In order to be able to improve the 2% settling time, the effects of a very long time constant τ_2 were compensated by digitally filtering the y^m signal. The phase advance filter used for this purpose, is presented in Fig. 13 and contains three coefficients c_0, c_1, d_1.
At any time the output of the filter is given by:

$$y_k^f = c_0 y_k^m + c_1 y_{k-1}^m - d_1 y_{k-1}^f$$

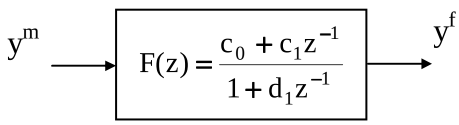

Fig. 13. Digital filter compensating for the dynamic effects of a long time constant.

Experimental set-up is described in Fig. 14. The actual flow is delivered by a fast gas flow meter based on the measurement of differential pressure (Crucis) and is registered by a specially developed Labview application.

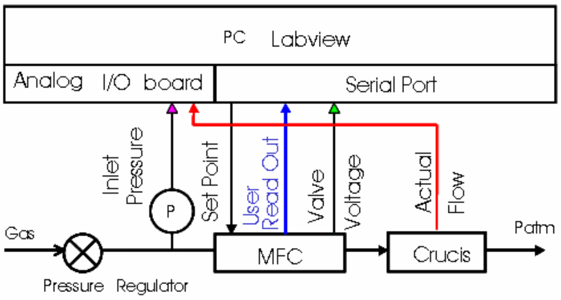

Fig. 14. Experimental set-up. Actual flow is delivered by a fast gas flow meter based on measurement of differential pressure (Crucis).

With the inclusion of filter F, the open-loop system can then be considered as a first order system (with time constant τ_1) and the RST controller synthesis procedure described in section 3.3 can be applied.

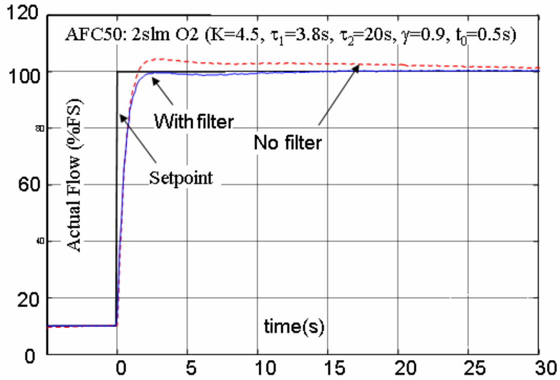

Fig. 14. Step response of the MFC, 2slm O2: with the filter 2% settling time is 2 s and there is no overshoot.

This gives: $A = 1 + a_1.z^{-1}, B = b_1.z^{-1}$ with $a_1 = -\exp(-T_e/\tau_1)$ and $b_1 = K(1 + a_1)$ where Te is the sampling period

If a first order response (with t_0 as time constant) is chosen as the transient closed-loop response, we obtain:

$$P° = (1 + p_1 z^{-1}) = [1 - \exp(-T_e/t_0)z^{-1}]$$

Where t_0 is the time constant of the closed loop system.

Solving the Diophantine equation (10) gives:

$$S_1 = 1 \text{ and } R_1 = (1 + p_1)/b_1$$

Finally polynomials S, R and T can be written:

$$S = S_1(1 - z^{-1}) = (1 - z^{-1})$$

$$R = A.R_1 = r_0 + r_1.z^{-1}, T = r_0 + r_1$$

with $r_0 = (p_1 + 1)/b_1$, $r_1 = a_1(p_1 + 1)/b_1$

At time k.Te, and according to expression (6), it comes that the command value applied to the valve becomes:

$$u_k = (r_0 + r_1)y_k^c + r_0 y_k^f + r_1 y_{k-1}^f + u_{k-1} \qquad (11)$$

The numerical value u_k is bounded. In case the limits should be reached, u_k is maintained to its limits in exoression (11).

Fig. 15 illustrates the actual flow for a step response of the MFC when applying the proposed control strategy. The saturation of the command is not reached in the present case. The desired performances are obtained as regards stability, precision and 2% settling time.

6. Conclusion

For some time, Mass Flow Controllers have been the most effective means of precisely controlling gas flow in processes used in semiconductor industry. Controlling such a device to obtain high dynamic performance is a challenge as MFC devices are non linear mechatronic systems in which the thermal sensor generally gives slow response times as compared to flow rate settling times.

Recently introduced, digital technology provides better flexibility for calibration and the control process, better communication, better monitoring and better optimization of performances. In this paper we show how a digital controller may be mathematically computed for MFCs once the dynamic characteristics of the open-loop system have been identified. The proposed control method goes beyond prior art control methods since, whatever the order of the model, the control law can be exactly computed and a desired transient response of the device imposed in closed-loop operation. However in practice, non linearity and modeling errors may limit linear control performances. Thanks to the digital technology the control parameters can be stored and adapted on line, depending on the MFC utilization.

In order to provide always better quality of services to end-users a great deal of research effort has been devoted to improving the characteristics of MFC components [4][8][9]: faster sensor, piezoelectric valve, new anti-corrosive materials.

Acknowledgements

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