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On possibilities of the practical implementation of balance-based adaptive control methodology

by

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Abstract: This paper deals with two approaches to the practical implementation of the Balance-Based Adaptive Controller(B-BAC): the low-level PLC-based approach of the explicit form of the B-BAC and the high-level PC-based one in the form of the general "virtual controller". In both cases, we discuss the details of meeting the general requirements of a particular practical implementation. We also consider the implementation aspects that are independent of the implementation, such as development of the front panel, saturation of a manipulated variable, on-line measurement and data acquisition, implementation of the on-line estimation procedure, bumpless switching between the automatic and manual mode, etc. Additionally, we present how to derive both the general form and the final explicit form of the B-BAC on the example of a biotechnological process and how to apply these forms in the particular practical implementation.

Keywords: model-based adaptive control, practical implementation, bumpless switching, virtual controllers, programmable logic controllers, recursive least-squares estimation.

1. Introduction

Although the majority of control applications in the process industries still rely on the conventional PID controller (Seborg, 1999), it must be said that model-based approaches promise great improvement in control efficiency and have become an important area of research activities (e.g. Lee and Sullivan, 1988; Isidori, 1989; Bastin and Dochain, 1990; Rhinehart and Riggs, 1990; Henson and Seborg, 1997; Joshi et al., 1997; Seborg, 1999). Unfortunately, those research activities mainly concentrate on theoretical considerations and simulation experiments and even if practical experimental results are presented, the implementation problems are usually not discussed. It is fully acceptable at the preliminary theoretical stage of the development of every new control strategy, but it must be kept in mind that any control algorithm must be finally applied in industrial control loops. Thus, the issues of practical implementation must be always considered to meet the requirements that ensure the practical application in the control loop.

The popularity of the conventional PID controller results mainly from two reasons. The PID controller is surely the most general approach for developing the control loop. The form of this control algorithm is independent of a process that must be regulated and the dynamics of this process influences only the final tuning of the PID controller. Additionally, there are very common and easy-to-apply rules for the tuning procedure and thus it is very easy to apply the PID controller in the practice. This is quite different from the case of any model-based control algorithm, because such an algorithm is always based on a form of the mathematical model of a process. Even if this form is partially known, it is usually unique and thus the final control algorithm is not general but strictly dedicated to regulate a particular process. The second reason for such a great popularity of the conventional PID controller is surely its very large accessibility in modern control equipment. Almost every PLC device provides the block of more or less advanced PID controller and thus the application of this controller is straightforward. If the user wants to apply any model-based control algorithm, he or she has to implement it individually.

The B-BAC methodology has been described in details in Czeczot (2006a,b) and its control performance has been demonstrated by simulation in application to different processes, such as the heat exchange and distribution processes (Czeczot, 2001, 2005), nonisothermal chemical reactor with the cooling jacket (Czeczot, 2006b) and the neutralization process (Czeczot, 2006a). In the author's opinion, it proves the generality of the considered methodology and even if it surely has the model-based origin, this generality is more comparable with the generality of the conventional PID controller. It ensures that it is possible to implement the B-BAC as the general control algorithm and then to apply it to regulate a particular process. In this paper, we discuss the most important properties of this controller in terms of the requirements of such an implementation.

2. The idea of the B-BAC methodology

2.1. Short introduction to the B-BAC methodology

The B-BAC methodology is based on the simplified and general form of the balance-based equation describing directly a controlled variable Y:

$$\frac{dY(t)}{dt} = \frac{1}{V(t)}\underline{F}^T(t)\underline{Y}_F(t) - R_Y(t), \tag{1}$$

where the vector product $\underline{F}^T(t)\underline{Y}_F(t)$ represents mass or energy fluxes, correlated with a controlled variable Y, that are incoming to or outcoming from a tank, $V(t)$ [m^3] is the volume of a tank and $R_Y(t)$ is the unknown time-varying parameter representing unknown process nonlinearities, as well as the modeling uncertainties, such as the different order of process dynamics, omitted or unrecognizable balance terms or variable volume V if a basic balance equation was not rearranged to the form that includes the volume balance equation.

During the synthesis of the B-BAC the manipulated variable must be chosen as one of the elements of the vectors $\underline{F}(t)$ or $\underline{Y}_F(t)$, while their other elements as well as the tank volume $V(t)$ must be measurable on-line or known, according to the choice of the user.

The value of the unknown parameter $R_Y(t)$ can be estimated on-line at discrete moments of time by the scalar form of the recursive least-squares method with the forgetting factor α. This estimation procedure is based on the discretized form of Eq. (1) (Czeczot, 1997). After defining the auxiliary variable y^i:

$$y^i = \gamma V^i \left(Y^i - Y^{i-1}\right) - T_R \underline{F}^{T,i} \underline{Y}_F^i, \tag{2a}$$

we can suggest the equations for the estimation procedure:

$$P^i = \frac{P^{i-1}}{\alpha} \left(1 - \frac{V^{i\,2} T_R^2 P^{i-1}}{\alpha + V^{i\,2} T_R^2 P^{i-1}}\right), \tag{2b}$$

$$\hat{R}_Y^i = \hat{R}_Y^{i-1} - V^i T_R P^i \left(y^i + V^i T_R \hat{R}_Y^{i-1}\right), \tag{2c}$$

where i denotes the discretization instant and T_R is the sampling time. The gain parameter γ allows for limiting the transient value of the approximation of the time derivative in the cases when the measurement data are noisy or when the system is strongly nonlinear with very fast dynamics. The value of this parameter can be chosen as $\gamma \in (0, 1]$ and if it is set as $\gamma < 1$, it does affect the value of y^i and consequently the estimation accuracy, but only in the transients. The problem of the choice of the initial values of P^0 and $\hat{R}_Y^0$ is discussed in details in Section 4.4. The scalar form of the estimation procedure ensures very accurate estimation results without any additional excitation input signal that is usually necessary to guarantee the persistence of excitation for the on-line multiparameter identification (Dasgupta et al., 1991). It was proved by Czeczot (2006a) that even in the steady state the estimate $\hat{R}_Y$ always converges to its true value R_Y with the rate of convergence depending directly on the value of the forgetting factor α.

For the synthesis of the final form of the B-BAC we apply the linearization technique (Isidori, 1989) in the form dedicated to the systems whose relative order is one (Bastin and Dochain, 1990). If we assume that the control objective is to keep the controlled variable Y equal to its setpoint Y_{sp}, we can suggest the stable first-order closed-loop dynamics with λ as the positive tuning parameter:

$$\frac{dY(t)}{dt} = \lambda \left(Y_{sp} - Y(t)\right) \tag{3}$$

and then, after combining Eqs. (1) and (3) and replacing the unknown parameter R_Y by its on-line estimate $\hat{R}_Y$ we can obtain the final and general discrete-time form of the B-BAC:

$$\underline{F}^{T,i}\underline{Y}_F^i = \lambda V^i \left(Y_{sp} - Y^i\right) + V^i \hat{R}_Y^i. \tag{4}$$

Once a manipulated variable has been chosen, the above equation can be rearranged into the explicit form of the B-BAC control law, which is always possible because the balance-based origin of the simplified model (1) ensures that it always has the affine form. This explicit form depends on the particular process that is to be controlled and thus it cannot be given in the general form.

Let us note that Eq. (1) can be always satisfied since it is always possible to find the value of R_Y(t) that satisfies this equation at the particular moment of time. When we assume that the value of R_Y(t) can vary in time, it is obvious that we can ensure that Eq. (1) can be satisfied at each moment of time by the appropriate choice of the current value of R_Y(t). This shows that the general dynamic Eq. (1) describes the dynamics of a controlled variable with high accuracy when the appropriate on-line estimation procedure (2a-2c) is employed (Czeczot, 2006a).

2.2. Synthesis of the B-BAC - illustrative example

In this paper the continuous fermentation process (for instance, bacterial production of amino acids, e.g. lysine), taking place in the reactor tank with the constant volume V, is considered as the illustrative example both for the synthesis and for the implementation issues of the B-BAController. The simplified diagram of the process is presented in Fig. 1. We assume that the form of its complete mathematical model is unknown. Especially, there is a large uncertainty with respect to the nonlinear description of the biological reaction taking place. Moreover, only the inlet and the outlet substrate concentrations (S_{in} and S) and the flow rate F are available for on-line measurement. Although these limitations are very restrictive and realistic from the practical point of view, they are acceptable for the B-BAC methodology.

In practical applications of this system, the yield-productivity conflict occurs and thus there is a need to manage this problem by a properly designed control loop. It was shown (Bastin and Dochain, 1990; Van Impre and Bastin, 1995) that the effective control of the lysine production process consists in regulating the outlet substrate concentration $S(t)$ at the properly chosen set point during the bioreactor activity. Thus, according to the B-BAC methodology, we can define the controlled variable $Y(t) = S(t)$ and the control goal $Y(t) = Y_{sp}$. The

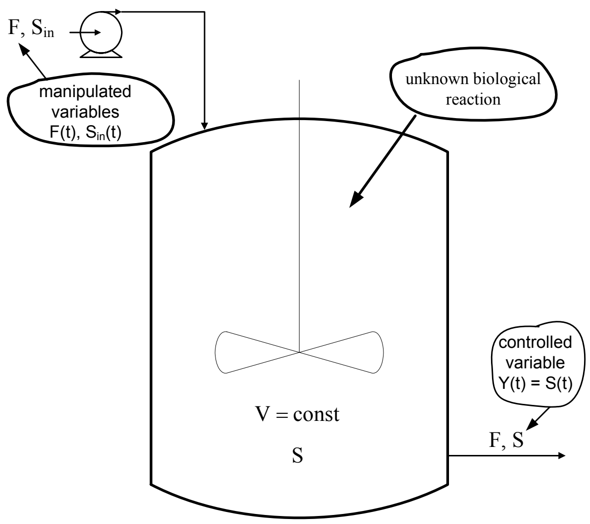

Figure 1. Simplified diagram of the fermentation process

simplified model of our process, given in the form of Eq. (1), can be derived from the general mass conservation law written for the substrate:

$$\frac{dY(t)}{dt} = \frac{1}{V} F(t) \left(S_{in}(t) - Y(t)\right) - R_Y(t). \tag{5}$$

In this model, the parameter R_Y represents the nonlinearities resulting from the unknown description of the biological reaction taking place and from the modeling uncertainties.

For our control goal we have two possible manipulated variables: the flow rate F and the inlet substrate concentration S_{in}. We can also define the vectors $\underline{F}(t)$ and $\underline{Y}_F(t)$ in the following ways:

$$\underline{F}(t) = [F(t)]^T, \quad \underline{Y}_F(t) = [S_{in}(t) - Y(t)]^T \tag{6a}$$

$$\underline{F}(t) = [F(t); \ \ -F(t)]^T, \quad \underline{Y}_F(t) = [S_{in}(t); \ \ Y(t)]^T. \tag{6b}$$

Let us note that although both structures and numbers of elements of the vectors $\underline{F}(t)$ and $\underline{Y}_F(t)$ are different, they still represent the same simplified dynamic model of the process (5). Every element of each vector can be easily computed because all signals are accessible for the on-line measurement. The choice of the particular definition depends on the implementation requirements that are discussed in details further in the paper. Yet, both forms of the vectors (6a-6b) can be directly applied for the estimation procedure (2a-2c) as well as for the general form of the B-BAC (4).

If we want to derive the final and explicit form of the B-BAC, we have to define the manipulated variable and to rearrange Eq. (5) according to the B-BAC methodology. It leads to two forms depending on the choice of the manipulated variable:

- for the flow rate F as the manipulated variable:

$$F^i = \frac{\lambda V \left(S_{sp} - Y^i\right) + V \hat{R}_Y^i}{S_{in}^i - Y^i}; \tag{7a}$$

- for the inlet substrate concentration S_{in} as the manipulated variable:

$$S_{in}^i = \frac{\lambda V \left(S_{sp} - Y^i\right) + V \hat{R}_Y^i + F^i Y^i}{F^i}. \tag{7b}$$

In both cases, the final form of Eqs. (2a-2c) for the estimation procedure is unaffected by the chosen definition of the vectors $\underline{F}(t)$ and $\underline{Y}_F(t)$. Thus, we can write one final form of this procedure, valid for both B-BACs (7a-7b). We define the auxiliary variable y^i:

$$y^i = \gamma V^i \left(Y^i - Y^{i-1}\right) - T_R \left(F^i \left(S_{in}^i - Y^i\right)\right), \tag{8}$$

and then we use Eqs. (2b) and (2c) to determine the value of $\hat{R}_Y^i$.

The control performance of the B-BAC control law in application to this example process can be found in Czeczot (1999).

3. Practical implementation of the B-BAC controller

3.1. Low-level PLC-based implementation

Nowadays, the stand-alone Programmable Logic Controllers (PLC) are applied in the vast majority of the practical industrial control loops due to their flexibility, reliability and standard low-level programming languages, such as the ladder diagram or the assembler instruction list. The limited applicability of these devices results directly from the limited choice of the function blocks that can be used while programming as well as from the limited computational capacity. Practically, if the user decides to implement any nonlinear advanced control algorithm, he or she has to write the dedicated program in the form of the block diagram that contains block symbols for arithmetic operations (addition, subtraction, multiplication, division and, in more advanced cases, trigonometric and log functions, as well as the square root, comparison and conversion functions) (Trybus, 1992; Batten, 1994; Webb and Reis, 1999). If this control law with all the possible nonlinear calculations and estimation procedures are very complex, it is very difficult to write such a program in the form of the block diagram. In some cases, it is possible to use a computer-type language, which is usually similar to BASIC and allows for the programming in the form of the instruction sequences employing English statements and instructions. However, in both cases the complex calculations require more RAM memory and more computation time. The increase of the computation costs results in the limitation of the sampling time and consequently the implemented advanced control algorithm can be unable to ensure desirable control performance.

The B-BAC methodology is based on the very simple and general model of a process in the form of the scalar dynamic Eq. (1). Its adaptability results from the on-line estimation of the only one single unknown parameter R_Y, which ensures that the recursive least-squares procedure is always applied in the scalar form (2a-2c), which significantly decreases the complexity of the calculations. However, even in this case the limitations of the PLC's, described above, disable the implementation of the B-BAC in the general form (4). The general form of the estimation procedure (2a-2c) is also very inconvenient because Eq. (2a) includes the vector product. Fortunately, since Eq. (1) has always the affine form, after the manipulated variable has been chosen, it is always possible to derive the final and explicit form of the B-BAC and the final form of the estimation procedure. Both these forms are quite simple and they can be computed by applying only the basic arithmetic functions. In Subsection 2.2, we showed from an example how to derive such an explicit form of the B-BAC along with the final form of the estimation procedure. If the user wants to implement the B-BAC for that example, he or she has to use the estimation scheme (8), (2b,2c) and to choose between the control laws (7a) and (7b). This is the only approach for the practical low-level PLC-based implementation However, the disadvantage of this approach results from the fact that the program written for one application is useless for the other ones. For each particular application, the explicit and final form of the B-BAC, as well as of the estimation procedure, must be derived separately. For example, for our system described in Subsection 2.2 the final form of the estimation procedure (8), (2b,2c) remains the same but the final form of the B-BAC (7a-7b) depends on the choice of the manipulated variable. Thus, even in the case of this simple example, this choice determines at least the part of the program and this program is not directly portable to other control systems.

The other important inconvenience of the considered PLC-based implementation results from the lack of the flexible front panel. If any front panel exists at all, it is fixed and cannot be re-defined and adapted to the requirements of the particular application. However, nowadays the commercial PLC's can be used in complex network systems basing on the TCP/IP protocol and thus the SCADA system, implemented on a workstation, can stand for the front panel. Since the SCADA systems are programmed in the high-level and usually graphical environment, this front panel can be fixed by the user according to the particular requirements.

3.2. High-level PC-based implementation

Some limitations discussed for the low-level PLC-based implementation are not significant if we consider the high-level implementation of the control algorithm in the form of the PC-based "virtual controller", where the algorithm is written in a programming language such as C++, Fortran, Visual Basic, LabView, etc. These applications are implemented on low-cost PCs (personal computers) or workstations and they provide full connection with process sensors and actuators via standard I/O plug-in PC-board cards with signal conditioning external modules or via TCP/IP network connection (Wolfe, 1993; Metzger, 1998, 1999, 2000). Additionally, virtual controllers usually provide real-time realization as well as the considerable flexibility in programming the interactive and user-friendly graphical interface.

The possibility of application of any high-level programming language with all the programming and data structures ensures that even very complex estimation and control algorithms can be implemented in the form of the virtual controller. In the case of the B-BAC methodology, we can benefit from its generality and implement directly the vector form of the estimation procedure (2a-2c) and of the control law (4). However, if we wanted to design the possibly most general implementation with a general front panel and with the possibilities of free connection of any measurement signals, it would be unnecessarily complex and user-unfriendly. Thus, our recommendation is to prepare the procedure or the function block in which only the calculations of the estimation procedure and of a manipulated variable are implemented. Actually, this approach benefits from the fact that the general form of the estimation procedure (2a-2c) and of the control law (4) remain unaffected by the requirements of a particular control application. Only the definition of the vectors $\underline{F}(t)$ and $\underline{Y}_F(t)$ can vary according to these requirements (see the example in Subsection 2.2) and thus our B-BAC calculating block should provide the following features:

- the ability to define the number of elements of the vectors $\underline{F}(t)$ and $\underline{Y}_F(t)$ (note that both vectors are always of the same length),
- the ability to define the combinations of the measurement signals and their connection to the appropriate elements of the vectors $\underline{F}(t)$ and $\underline{Y}_F(t)$,
- the ability to choose the manipulated variable as one of the elements of the vectors $\underline{F}(t)$ or $\underline{Y}_F(t)$ (the choice of a manipulated variable determines the form of the vectors $\underline{F}(t)$ and $\underline{Y}_F(t)$ and, consequently, the computation of the control law (4) and it should be possible without any interference into the program code).

This block can be used in a number of control applications, always with the front panel and with the connections to the external measurement signals and actuators designed separately for each control system only if it provides the following input and output terminals:

Inputs

- the elements of the vectors $\underline{F}(t)$ and $\underline{Y}_F(t)$, computed as the combinations of the measurement signals - both vectors have always the same number of elements and the B-BAC function block should calculate this value on the basis of the defined form of these vectors,

- the terminal that allows to choose the element of the vector $\underline{F}(t)$ or $\underline{Y}_F(t)$, which includes a manipulated variable,
- the terminal that allows for the switching between the automatic and the manual mode,
- the terminal for the volume of a reactor tank V - if this value varies in time, there should be connection with the measurement data of the current value of V,
- the settings of the estimation procedure (2a-2c) and of the B-BAC control law (4): the set-point Y_{sp}, the tuning parameter λ, the sampling time T_R, the forgetting factor α, the initial value of $\hat{R}_Y^0$ and the initial value of the parameter P^0 (these parameters should be set in the properly designed front panel).

Outputs

- the value of a manipulated variable computed by the B-BAC function block,
- the current values of the control error and of the estimated value $\hat{R}_Y^i$ (these outputs are not necessary for the correct work of the B-BAC controller but they can be useful for the monitoring of a process).

4. Additional remarks independent of the implementation

In the previous section, we discussed the specific problems and requirements for each considered implementation approach. However, there are also some other problems and requirements that are common in both cases and they are discussed in this section.

4.1. Development of the front panel

The control elements and the indicators located in the front panel of our B-BAC controller have to be chosen very carefully to combine the flexibility of the controller with the user-friendly and convenient layout. In our opinion, these requirements can be met if the front panel provides the following functions:

- direct choice of a manipulated variable as one element of one of the vectors $\underline{F}(t)$ or $\underline{Y}_F(t)$,
- switching between the automatic and the manual mode,
- adjusting the B-BAC (4) settings, such as the set-point Y_{sp}, the tuning parameter λ and the sampling time T_R,
- adjusting the parameters of the estimation procedure (2a-2c), such as the forgetting factor α, the initial values of $\hat{R}_Y^0$ and the initial value of the parameter P^0.

It would be also convenient to include at the front panel the indicators that allow the user to observe the current values of the control error, of controlled and manipulated variables, and of the estimated parameter $\hat{R}_Y^i$. Moreover, the application of the B-BAC should enable storing the data in the text files for the monitoring of the process history.

4.2. Saturation of a manipulated variable and the integral action

In practice, there is always a limitation of a manipulated variable, which can result from the limitations of an actuator or from the saturation of a control output. This limitation is not specific to any control algorithm but it results from the properties of the controlled process. Thus, in the practical implementation, the value of a manipulated variable calculated on the basis of the B-BAC control law must be additionally bounded by the appropriate conditioning structure.

Due to the compensating properties of the estimation procedure (2a-2c) (Czeczot, 2006a), the B-BAC always eliminates the steady-state control error in the closed loop and thus there is no need to include any additional integral action to the control law. Consequently, there is no need to implement any anti-wind-up procedure.

4.3. On line measurement and data acquisition

The B-BAC methodology provides the feedforward action by including the disturbances in the vector product $\underline{F}^T(t)\underline{Y}_F(t)$ of Eq. (1). This action is introduced in a very natural way, because it results directly from the general mass or energy balance considerations. This feature allows for the improvement of the control performance but, apart from the measurement of a controlled variable, it also requires the additional measurement data for these disturbing signals, which must be acquired by the additional analog I/O modules connected to some sensors and transducers. In more complex cases, when a significant number of disturbing signals must be measured, it results in higher costs of a control system in comparison with the conventional PI controller without any feedforward action.

Again, contrary to the PI-based control systems, there are two values of the manipulated variable in the application of the B-BAC methodology. One is the value calculated from the control law, which stimulates an actuator by the analog output. However, due to the dynamics of an actuator, in the transients this value differs from the current value of a manipulated variable, forced by an actuator and this value can be acquired only by the on-line measurement. Because the estimation procedure needs the value of a manipulated variable, we recommend using the measured value rather than the "theoretical" one, calculated by the B-BAC control law. This ensures that the estimation procedure partially compensates also for the dynamics of an actuator.

Another issue that must be discussed in this subsection is the influence of the measurement noise correlated with disturbing signals and with controlled and manipulated variables. The proper choice of the value of the forgetting factor α for the estimation procedure allows for decreasing the influence of the measurement noise on the estimation accuracy and, consequently, on the B-BAC control performance. However, in practical cases, we recommend filtering of the measurement data rather than applying larger values of α. Increasing the value of α allows for decreasing the influence of the measurement noise, but the closed loop dynamics deteriorates, because the estimate converges slower and the simplified model (1) is not updated accurately at each moment of time. It is much better to adjust the value of α at a possibly low lewel (for example $\alpha = 0.1$) and, instead, to apply analog or digital filters for decreasing the influence of the measurement noise. This ensures that the estimate converges fast and thus the simplified model (1) follows the variations of a manipulated variable and of disturbances with higher accuracy. Furthermore, the application of these filters allows also for decreasing the direct influence of the noisy measurement data on the control performance because the same measurement data is applied not only for the estimation procedure but also for the B-BAController. It should be also said that the adjusting of the forgetting factor α should be correlated with the tuning of the B-BAC (setting the tuning parameter λ) but it is difficult to give any general rules for this procedure. The optimal choice of the values of α and λ always depends on the dynamics of a particular process to be controlled and on the impact of the measurement noise.

4.4. Implementation of the estimation procedure

For the practical implementation of the estimation procedure (2a-2c) it is very important to note that the procedure itself has a recursive form so there is a need to store the current values of the parameter P^i and of the estimate $\hat{R}_Y^i$ in the memory. These values must be updated at each run of the programming loop before the control law is computed. The other difficulty, which results from the recursive nature of the calculations, is the problem of the initial values. The initial value P^0 should be chosen as $P^0 >> 1$, but this choice has no significant influence on the estimation accuracy in the case of the scalar form of the RLS equations (2a-2c) (Czeczot, 2006a). On the other hand, the choice of the value $\hat{R}_Y^0$ has very significant influence but only at the initial stage of the estimation run. Although the estimate $\hat{R}_Y^i$ always converges to its true value $R_Y(\mathrm{t})$, there is a transient at the initial stage of the estimation due to the improper choice of the initial value $\hat{R}_Y^0$. Thus, if we want to avoid the influence of this estimation inaccuracy on the control performance, there is a need to start the estimation procedure in the open loop and then to close the control loop with the B-BAC after the estimate has converged. The results of the simulation experiments, presented in the next subsection, additionally illustrate this feature.

4.5. Switching between the manual and the automatic mode

The idea of the bumpless switching (Hanus et al., 1987; Trybus, 1992) can be put in one sentence: when the controller is switched between the manual and the automatic mode, the value of a manipulated variable, calculated from the control law, must be the same as the value manually adjusted by the user. In the case of the advanced adaptive model-based control techniques, it is ensured only if the internal model matches the output of a process with a possibly high accuracy. In other words, the internal model must be updated on-line by an adaptation technique not only in the automatic mode (closed loop) but also in the manual mode (open loop). Thus, the estimation procedure, which provides the adaptation, must be carried out even if the controller is switched into manual mode.

In the case of the B-BAC methodology, the bumpless switching is possible because the control law is based on the general and simplified dynamic model of a process (1). This model describes a process with high accuracy only if the value of the estimate $\hat{R}_Y^i$ is updated on-line with high accuracy, which depends on the choice of the value of the forgetting factor α (Czeczot, 2006a). As said in the previous subsection, this value should be possibly small even in the case when the significant measurement noise occurs. Otherwise, the convergence time can be significantly long and the bumpless switching could not work properly if the controller is switched into the automatic mode before the estimate $\hat{R}_Y^i$ has converged to its right value.

Figs. 2a-2c shows the simulation results of the control performance of the B-BAC (7a) in the application to the example process (see Fig. 1 and Appendix). We consider two cases: with and without bumpless switching. In both cases, the experiment has been carried out in the same way. First, the B-BAC (7a) is operated in the open loop (manual mode with constant and manually adjusted manipulated variable F). At $t = 5$, control loop is closed (switching into the automatic mode) and at $t = 10$ the set point Y_{sp} is changed. Then, at $t = 20$ the controller is switched into the manual mode again and the value of the manipulated variable F is slowly decreased manually. In the meantime, at $t = 25$, the additional disturbing step change of S_{in} is applied to the system. Finally, at $t = 30$, the B-BAC (7a) is switched into the automatic mode once again with the new, manually adjusted value of the manipulated variable F.

In case 1 the estimation procedure (8), (2b-2c) is computed both in the automatic and in the manual mode to allow for bumpless switching, which is contrary to the case 2, when it is computed only when the B-BAC (7a) works in the automatic mode. In both cases we have $\alpha = 0.1$ and $\gamma = 1$. The initial value $\hat{R}_Y^0$ was chosen incorrectly. Because in case 1 the estimation procedure (8), (2b-2c) is started at $t = 0$, the estimate $\hat{R}_Y^i$ converges to its true value when the process is operated in the open loop and when the B-BAController (7a) works in the manual mode, and thus the choice of the initial value $\hat{R}_Y^0$ has no influence on the control performance. In case 2, the estimation procedure (8), (2b-2c) is started after the B-BAController (7a) has been switched into the automatic mode at $t = 5$ and thus the estimate $\hat{R}_Y^i$ converges from the improper initial value $\hat{R}_Y^0$ to its true value in the closed loop, which significantly degrades the

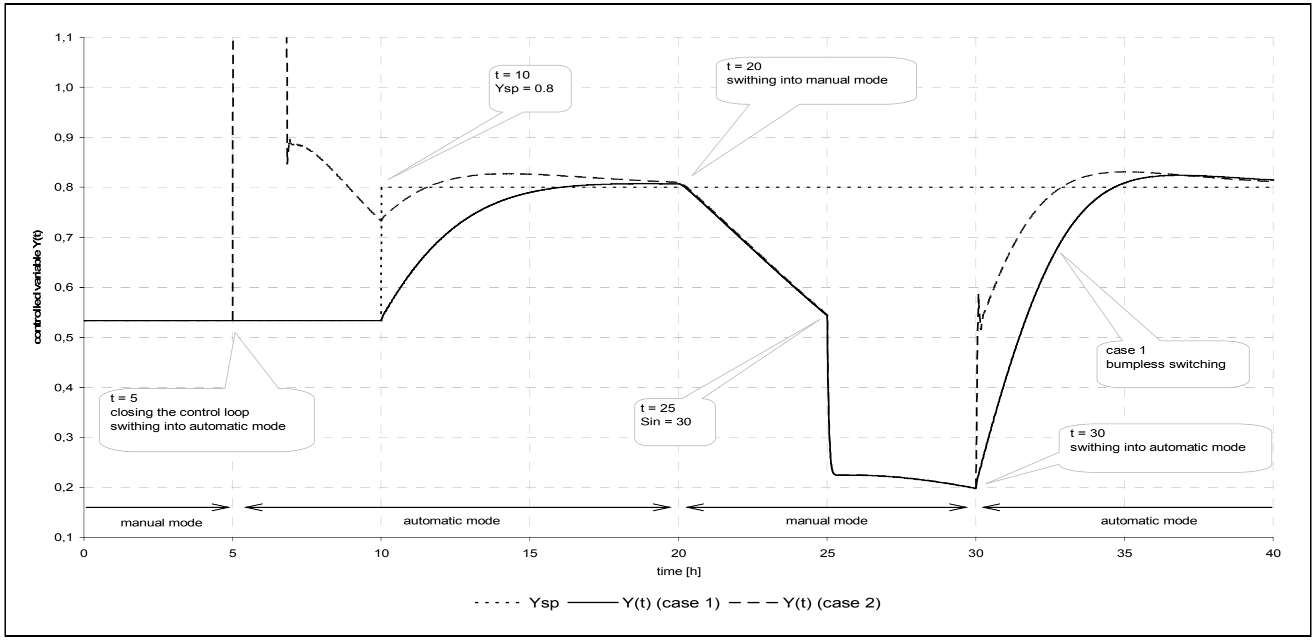

Figure 2a. Closed loop performance. (Case 1: with bumpless switching, Case 2: without bumpless switching). Controlled variable

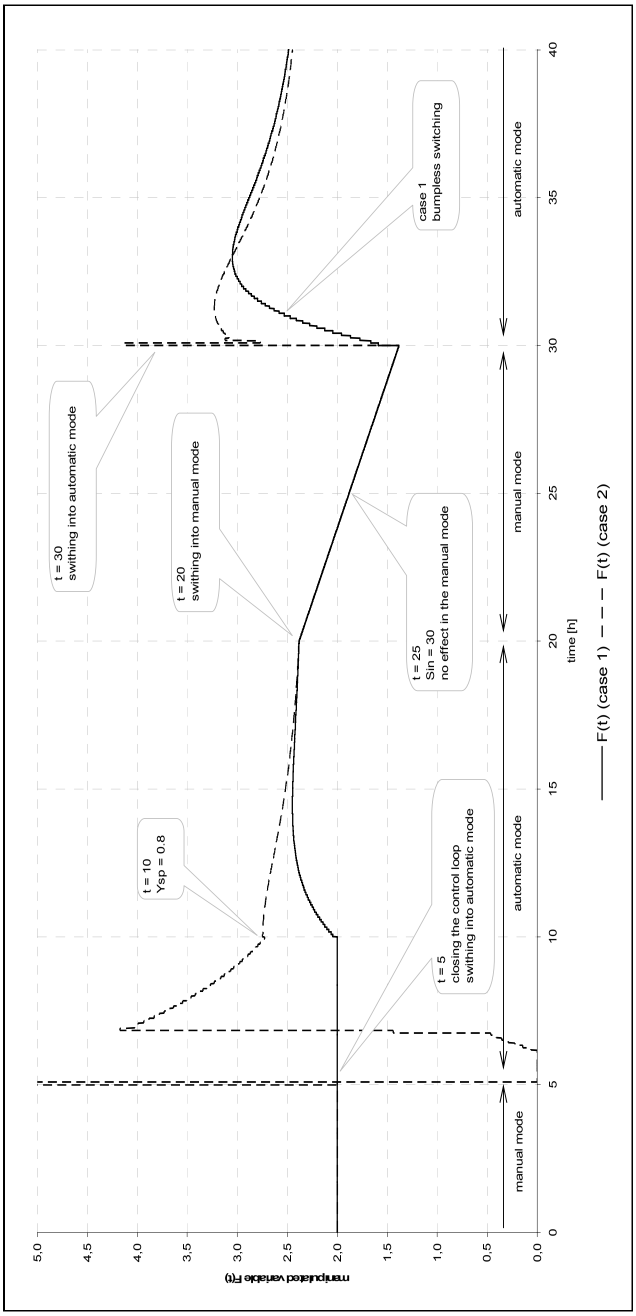

Figure 2b. Closed loop control performance. (Case 1: with bumpless switching, Case 2: without bumpless switching). Manipulated variable

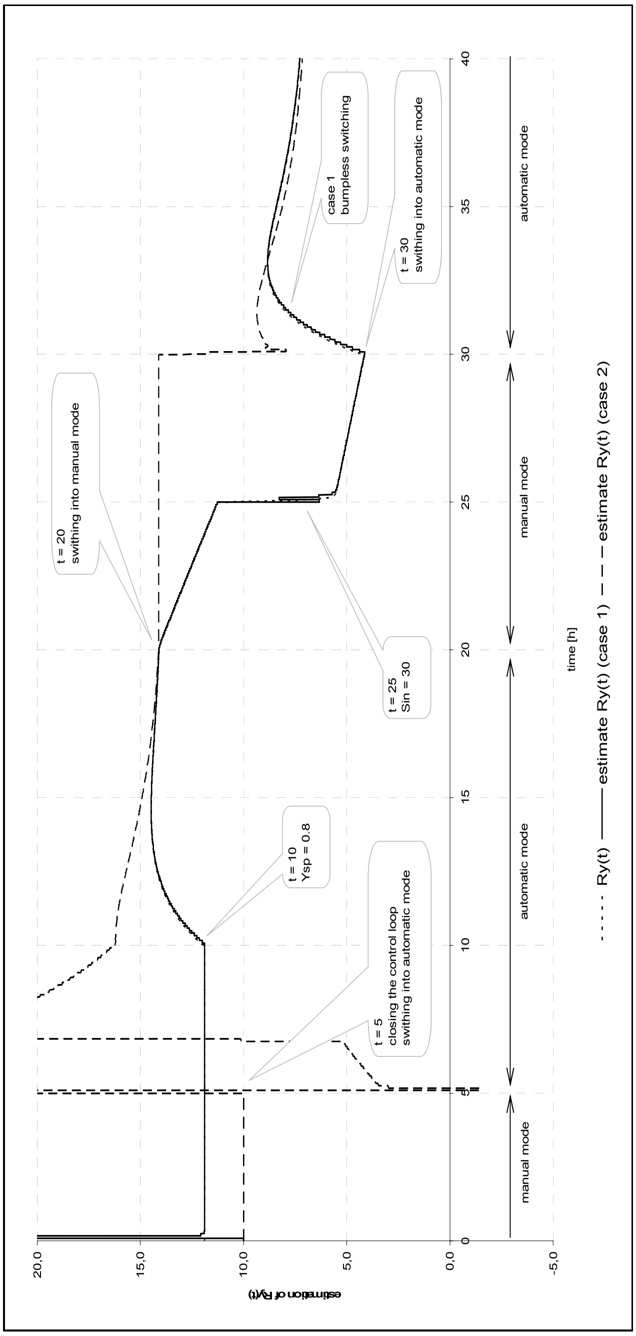

Figure 2c. Closed loop control performance. (Case 1: with bumpless switching, Case 2: without bumpless switching). Estimation accuracy

control performance. The B-BAC (7a) is switched again into the manual mode at $t = 20$ and let us note that the estimate $\hat{R}_Y^i$ is updated on-line with very high accuracy in case 1 while it remains constant in case 2, which results in the mismatch between the process output and the internal model. Consequently, it leads to the undesirable step change of the manipulated variable F, forced by the controller at $t = 30$ when it is switched into the automatic mode in case 2.

5. Concluding remarks

In this paper, we discuss the details of the B-BAC methodology in terms of the requirements of the practical low-level and high-level implementation approaches. We also suggest how to manage the problem of the bumpless switching and demonstrate it by simulation on the example of a biotechnological process. This process is also considered as the example for the synthesis of the general and the explicit form of the B-BAC and it is discussed, which form is suitable for the considered implementation approaches.

The author's experiences show that the B-BAC methodology can be directly applied to control a wide range of technological processes. Obviously, control performance can be significantly improved if the simplified model (1) describes a controlled variable with high accuracy, which is possible if the order of the process to be controlled is not significantly higher than one. However, even if a process has many first-order lags or if the output is significantly delayed, it is possible to tune the B-BAC more conservatively to obtain soft but slow and stable control. This results in the control performance that is comparable with the conventional PI controller tuned to ensure stable behavior.

The B-BAC methodology is the SISO approach. The MIMO extension is possible and a number of the control laws must be applied separately for each control loop. Every B-BAC must be derived on the basis of its own simplified model written in the form of Eq. (1) and the separate estimation procedure must be also applied for the on-line estimation of every parameter R_Y.

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Appendix

During the simulation experiments, we applied the mathematical model of the fermentation process (Bastin and Dochain, 1990), which consists of three nonlinear state equations describing, respectively, the biomass concentration X [g/L], the substrate concentration S [g/L], and the outgoing product concentration P [g/L]:

$$\frac{dX(t)}{dt} = \mu(t)X(t) - \frac{F(t)}{V}X(t),) \tag{A1}$$

$$\frac{dS(t)}{dt} = \frac{F(t)}{V}\left(S_{in}(t) - S(t)\right) - k_1\mu(t)X(t) - k_2\nu(t)X(t), \tag{A2}$$

$$\frac{dP(t)}{dt} = \nu(t)X(t) - \frac{F(t)}{V}P(t). \tag{A3}$$

The specific growth rate μ [1/h] and the specific production rate ν [1/h] are described by the following nonlinear expressions:

$$\mu(t) = \mu_{\max}\frac{S(t)}{K_M + S(t)}, \tag{A4}$$

$$\nu(t) = \begin{cases} S(t)\left(\nu_0 - \nu_1 S(t)\right) & 0 \leqslant S(t) \leqslant \frac{\nu_0}{\nu_1} \\ 0 \quad S(t) > \frac{\nu_0}{\nu_1} \end{cases} \tag{A5}$$

where:
F[L/h] – volumetric flow rate, V[L] – volume of the bioreactor tank, S_{in}[g/L] - inlet substrate concentration, k_1, k_2 [-] – yield coefficients, μ_{max} [1/h] – maximum specific growth rate, K_M [g/L] – saturation constant, ν_0, ν_1 – constant parameters.

The process has been simulated with the following values of the parameters: $V = 10$, $\mu_{max} = 0.35$, $K_M = 0.4$, $k_1 = 0.4$, $k_2 = 0.05$, $\nu_0 = 15$, $\nu_1 = 5$, $F = 2$, $S_{in} = 60$.