Design of Identification Based Adaptive Control for Fermentation Process in Bioreactor

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***Abstract*—**The biochemical technology has been developing extremely fast since the middle of the last century. The main reason for such development represents a requirement for large production of high-quality biologically manufactured products such as pharmaceuticals, foods, and beverages. The impact of the biochemical industry on the world economy is enormous. The great importance of this industry also results in intensive development in scientific disciplines relevant to the development of biochemical technology. In addition to developments in the fields of biology and chemistry, which enable to understand complex biochemical processes, development in the field of control theory and applications is also very important. In the paper, the control for the biochemical reactor for the milk fermentation was studied. During the fermentation process, the biophysical quantities must be precisely controlled to obtain the high-quality product. To control these quantities, the bioreactor's stirring drive and/or heating system can be used. Available commercial biochemical reactors are equipped with open loop or conventional linear closed loop control system. Due to the outstanding parameters variations and the partial nonlinearity of the biochemical process, the results obtained with these control systems are not satisfactory. To improve the fermentation process, the self-tuning adaptive control system was proposed. The use of the self-tuning adaptive control is suggested because the parameters' variations of the studied biochemical process are very slow in most cases. To determine the linearized mathematical model of the fermentation process, the recursive least square identification method was used. Based on the obtained mathematical model the linear quadratic regulator was tuned. The parameters' identification and the controller's synthesis are executed on-line and adapt the controller's parameters to the fermentation process' dynamics during the operation. The use of the proposed combination represents the original solution for the control of the milk fermentation process. The purpose of the paper is to contribute to the progress of the control systems for the biochemical reactors. The proposed adaptive control system was tested thoroughly. From the obtained results it is obvious that the proposed adaptive control system assures much better following of the reference signal as a conventional linear control system with fixed control parameters.

***Keywords*—**Adaptive control, biochemical reactor, linear quadratic regulator, recursive least square identification.

I. Introduction

MILK is an excellent growing media for microorganisms, which means that fermentation can be carried out with different starter cultures producing a range of dairy products. One of the basic parameters for describing the starter culture is its ability to produce aromatic products. Thus, yoghurt and similar probiotic products have a distinctive odor and taste, which is attributed to the volatile/non-volatile acids and carbonyl products produced during fermentation. Among the milk beverages, kefir is widely known for its unique aroma and taste [1].

Large-scale production of kefir has been interfered with the problems involved in reproducing the kefir grains and producing a product with acceptable flavour and good conservation properties. During the fermentation several compounds are produced which give the kefir its distinctive taste. Some ingredients can be measured and in this way we determine the quality of the product. These ingredients are carbon dioxide (CO_2), proteins, fat, lactose, ethanol and lactic acid [2]. The CO_2 is the most significant growth and metabolism product of microorganisms. For understanding and applying the effects of this gas on the microbiological metabolism, it is necessary to monitor the level of dissolved CO_2 in the fermentation medium. Too low CO_2 concentration generates an insignificant flavor in the beverage, too high CO_2 concentration causes inhibitory effects for microorganisms. The fluctuations in CO_2 concentration can occur as a result of technological errors, or because of the unpredictable behavior of microorganisms. The generation of CO_2 during kefir manufacture presents some practical problems, since the microorganisms in the kefir continue to grow following packaging. Such fluctuations at the industrial level of milk beverage production are not desirable [3]. Due to all these facts, it is highly desirable to control CO_2 release with the appropriate control system. Unfortunately the majority of the bioreactors are not implemented by the control systems for CO_2 release. Several methods for measuring the content of CO_2 in the fermentation medium are known, but control procedures are rare and not described [4].

To maintain the desired CO_2 level in bioreactors, the open-loop control systems are mainly used. The reason for this is complicated tuning procedure of closed-loop controllers. Mathematical models of the bioreactors are namely non-linear with unknown and variable structure and parameters. Because of the non-linear dynamics of the bioreactors, the conventional linear controllers do not assure optimal control in the entire operating range.

The adaptive control systems represent an effective solution to the problem of different dynamics of the bioreactors in different operating points. The adaptation mechanism adjusts the controller's parameters to the dynamics of the controlled plant. In this way, the optimal operation in the entire operating range is ensured. There exist numerous adaptive concepts, which can be in general divided into two groups [5], [6]:

- Indirect methods, where one of the parametric

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identification methods is used to identify the parameters of a mathematical model of the controlled plant. After that, the identified mathematical model is used to calculate the parameters of the controller,

- and direct methods, which are used to directly calculate a controller output, mainly based on discrepancy of measured controlled plant's variables from calculated reference model's variables. By implementation of these methods, there is no explicit identification of the controlled plant parameters.

For needs of bioreactor's fermentation processes none of the methods were implemented already.

The indirect methods represent the theoretical fundaments for self-tuning control systems. In this case, the calculation of parameters of the adequate discrete controller is based on the identified parameters of the controlled plant obtained by one of the parametric identification methods. The beginning of the self-tuning control systems go back in 1979 [7]. The combination of the recursive least square identification method and the state-space controller proved to be the most successful. Self-tuning control systems have also some disadvantages. The main disadvantage of such indirect approach is inconsistency in assuring the stability of the complete adaptive system. The stability of self-tuning adaptive systems is assured only in case of simpler, less applicable, controller synthesis methods. Additional difficulties are caused by disturbances and non-modeled dynamics.

The principal aim of the present study was design and synthesis of the self-tuning control system for restrained CO_2 release. The proposed control system is based on the linear quadratic state-space regulator (LQ regulator). To calculate the parameters of the LQ regulator the structure and the parameters of the mathematical model of the bioreactor must be known. Least square identification method was used for the identification of the controlled plant parameters.

II. Mathematical Model of the Fermentation Process in Bioreactor

A bioreactor is a tank in which several biological reactions occur in a liquid medium [8]. Most industrial bioreactors are operated in batch or fed-batch mode to allow more efficient media utilization and to avoid sterility problems caused by continuous liquid removal. In batch operation, the bioreactor is initially charged with cells and medium containing essential substrates for growth. The bioreactors then evolve to a predetermined final time with no media feed or liquid withdrawal. Fed-batch operation differs from batch operation in that fresh media feed is continuously supplied [9].

Mathematical modelling of bioreactors is a challenging problem due to the complexity of cellular metabolism. The appropriate degree of model complexity is determined by factors such as the amount of fundamental knowledge, data requirements for model construction and validation, computational requirements, and the intended use of the model [9].

Almost all bioreactor's mathematical models are represented with a set of non-linear differential equations which relate many biological variables (the most important are concentration or volume of the biomass, growth limiting substrate and desired product). The modern bioreactors are equipped with stirrers and heaters which enable to influence the biochemical processes in the bioreactors. On this way additional energy (mechanical work or heat) is added to the bioreactor. These bioreactor's inputs could be used for control system design. Unfortunately none of the known bioreactor's mathematical models represent influence of the input control variables on the progress of the fermentation process [10].

In [11] the necessary simplified mathematical model of the bioreactor which enables the control system design and synthesis was developed by an intuitive approach. The inputs of the mathematical model are mixer's speed and heater's temperature. The output of the mathematical model is the CO_2 concentration. A simplified mathematical model was developed using a two stage procedure [11]:

1) determination of exponential functions which describe CO_2 release behavior in response to initial conditions by different constant process inputs,
2) determination of differential equations which describe CO_2 release according to changeable process inputs.

The exponential functions are described by:

$$\gamma(t) = K_s(1 - \mathrm{e}^{\frac{t}{T_s}}) \qquad (1)$$

where t is time variable, $\gamma(t)$ denotes CO_2 concentration and K_s and T_s are parameters describing the static and dynamic characteristics of initial conditions response by constant (unchangeable) process input.

The dynamical model which describes CO_2 release according to changeable process inputs is determined by a simplified 2-inputs 1-output model which consists of two parallel connected transfer functions. They describe an effect of heater's temperature and mixer's speed on CO_2 release. The mathematical model is shown in Fig. 1 where transfer function $G_1(s)$ describes the influence of mixer's speed and transfer function $G_2(s)$ the influence of heater's temperature on CO_2 release.

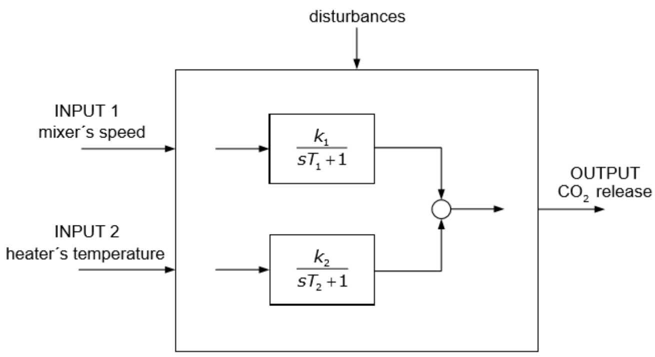

Fig. 1 Mathematical model of the influence of mixer's speed and heater's temperature on the CO_2 release of the fermentation process in bioreactor

$$G_1(s) = \frac{k_1}{sT_1 + 1} \tag{2}$$

$$G_2(s) = \frac{k_2}{sT_2 + 1} \tag{3}$$

A thorough analysis of the controlled plant on the basis of the developed mathematical model was performed. It was found out that only a single input of a fermentation process is sufficient to control the release of CO_2. The mixer's speed was selected due to quicker response and simpler actuator realization. Mixer's speed is the control variable and heater's temperature is considered as an additional disturbance. The accurate synthesis of the conventional proportional-integral-differential (PID) controller is not possible because the parameters of the mathematical model are unknown and varying.

III. Self-Tuning Control System

Instead of the conventional PID controller the self-tuning control system for the bioreactors's fermentation process is proposed. The self-tuning control system changes the parameters of the adjustable controller to assure desirable dynamics.

Self-tuning control system performs the tuning of the controller's parameters at the start of the operation and the adaptation of the controller's parameters to the changeable dynamics during the operation. On such way self-tuning controller assures optimal dynamics of the bioreactor in the entire operating range. Self-tuning control system consists of four modules:

- decision mechanism module,
- plant identification module,
- parameter tuning module and
- controller implementation module.

Block diagram of the self-tuning control system is shown in Fig. 2. The modules will be only briefly described.

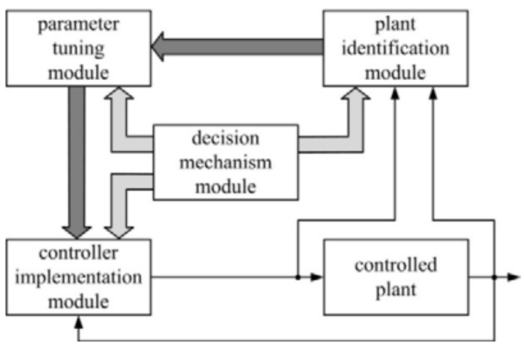

Fig. 2 The block diagram of the self-tuning control system

A. Decision Mechanism Module

Decision mechanism module coordinates operation of the others three modules. This module observes bioreactor's dynamics during operation. Based on this information *decision mechanism module* controls following main tasks:

- controlled plant identification,
- controller parameters' calculation and
- control law implementation.

B. Plant Identification Module

The parameters of the mathematical model of the bioreactor must be known to calculate the parameters of the implemented regulator. Plant identification module identifies parameters of the mathematical model of the controlled plant. To implement the identification the decision mechanism module coordinates the activities of the controller implementation module and plant identification module. Controller implementation module generates supplementary pseudo random binary signal for sufficient controlled plant input perturbation. On basis of these input changes plant identification module calculates discrete transfer function of the controlled plant. Well known recursive extended least square method (RELS) was used for parametric identification. To carry out the accurate identification by noised measured signals the added pseudo random binary input signal was used. By means of RELS identification method the input-output description of the controlled plant was identified. For the controller development the obtained discrete input-output model must be converted in the appropriate state-space model as described in [12].

C. Parameter Tuning Module

Parameter tuning module calculates the feedback gain **K** of the linear quadratic (LQ) regulator from the identified discrete transfer function. The procedure to calculate the feedback gain **K** consists of two parts. First, from the identified discrete transfer function the continuous state-space model of the controlled plant as described in [12] is calculated. Then, from the state-space model of the controlled plant [13] the parameters of the LQ regulator are calculated.

D. Controller Implementation Module

The controller implementation module implements the LQ regulator. The LQ regulator is based on the state-space description of the linear dynamic system described with:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \tag{4}$$

where $\mathbf{x}(t)$ is an n-vector of state variables, $\mathbf{u}(t)$ is an m-vector of input variables, **A** is the system matrix and **B** is input matrix. The matrices **A** and **B** have constant coefficients and are of dimensions nxn and nxm respectively and all possible pairs **A** and **B** are controllable.

The objective of the control law is to control the state-space vector $\mathbf{x}(t)$ from any initial value to the zero state vector in such a way that infinite-horizon quadratic cost function J defined with (5) will be minimized [13], [14].

$$J = \int_0^\infty \left(\mathbf{x}^{\mathrm{T}}(t)\mathbf{Q}\mathbf{x}(t) + \mathbf{u}^{\mathrm{T}}(t)\mathbf{R}\mathbf{u}(t) \right) \mathrm{d}t \tag{5}$$

Q is the symmetric positive semi-definite matrix and **R** is the symmetric positive definite matrix.

A feedback control law that minimizes cost function J is defined as:

$$\mathbf{u}(t) = -\mathbf{K}\mathbf{x}(t) \tag{6}$$

where $\mathbf{K}$ is the feedback gain given by:

$$\mathbf{K} = \mathbf{R}^{-1}\mathbf{B}^{T}\mathbf{P} \tag{7}$$

and $\mathbf{P}$ is found by solving the algebraic Riccati equation:

$$\mathbf{A}^{T}\mathbf{P} + \mathbf{P}\mathbf{A} - \mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^{T}\mathbf{P} + \mathbf{Q} = \mathbf{0} \tag{8}$$

IV. Results

To evaluate the applicability of the developed self-tuning control system for the bioreactor's fermentation process the proposed control system was tested. The production of kefir grains with traditional milk cultivation was studied in a RC1 reaction calorimeter (Mettler Toledo). RC1 is a computer-controlled laboratory batch reactor (V = 0.8 L), primarily designed for determination of the thermal characteristics of chemical reactions. It enables automatic performance and control of basic physical operations. The SevenMulti Apparatus (Mettler Toledo) measures conductivity in liquid media. It is connected to a personal computer, which records measurements with Lab X Direct pH 2.3 in a selected time period. A special ion-selective electrode is connected to the device [11].

For the studied bioreactor the parameters of the exponential function which describes the initial conditions response by constant process input (1) vary considerable [11]. The variation is in range:

$$K_s = 0.17 \ldots 0.23 \qquad T_s = 200 \ldots 400 \text{ (min)} \tag{9}$$

Fig. 3 shows the CO_2 release response in case when parameters of the controller were calculated on the basis of the identification of the controlled plant. From Fig. 3 the tracking of the prescribed dynamic trajectories is clearly seen.

V. Conclusion

In this study the use of identification based adaptive control for fermentation process in bioreactors is presented. The structure of the developed adaptive control system is discussed. Particular modules of the control system are described in details.

Obtained results show that the proposed self-tuning control system presents very effective solution for the improvement of the milk fermentation process. The synthesis of the control system is simplified and minimum error between reference and actual CO_2 values during a transient response and in a steady state is provided. A programmable logic controller could be used for the realization of the proposed control system.

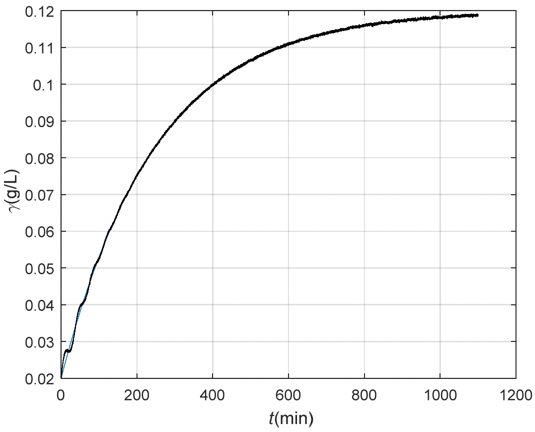

Fig. 3 Controlled CO_2 release

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