Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Chemical Engineering

Synchronization engineering

István Z Kiss

Synchronization of oscillatory chemical reactions play an important role in functioning of biological processes. Physiological condition is often achieved by an optimal level and structure of synchrony. When the synchronization breaks down, engineering techniques are needed to re-establish the structure. Closed-loop techniques for synchronization engineering can be used with linear and nonlinear feedbacks with delays. A framework for methodological design of the feedback allows adjusting phase difference between oscillators and generation of stable and itinerant clustering, desynchronization, and chimera states. The weak feedback signals allow for tuning synchronization rather than destroying the local dynamics. Phase model machinery for oscillatory processes in discrete units proves to be an important tool for design of engineering techniques.

Address
Department of Chemistry, Saint Louis University, 3501 Laclede Ave, St Louis, MO 63103, United States

Corresponding author: Kiss, István Z (izkiss@slu.edu)

Current Opinion in Chemical Engineering 2018, **28**:1–9

This review comes from a themed issue on **Reaction engineering and catalysis**

Edited by **Guy Marin**, **Grigoriy Yablonsky**, **Theodore Tsotsis** and **Marc-Olivier Coppens**

https://doi.org/10.1016/j.coche.2018.02.006

Introduction

Oscillatory behaviors (i.e. periodic variation of concentration of a chemical substance over time during the course of a chemical reaction) are widespread in biological systems, but also occur in complex chemical reactions [1]. As so elegantly developed by Nobel Laureate Ilya Prigogine, the far-from-equilibrium thermodynamic background for these processes requires a regulatory component (e.g. autocatalytic process in the Brusselator), and a presence of some additional substances that cause a delay in the regulation [2]. These conditions can give rise to oscillations even in relatively simple chemical reactions, but become common in biological systems where regulation and delay are central to the functioning of living entities. In classical chemical engineering, such fluctuations usually need to be suppressed, and thus proportional-integrative-differential (PID) controllers are applied to provide stable reactor operation. Conversely, stable rhythm is often required in biological systems, most prominently, a $5 billion industry developed for heart pacemakers [3].

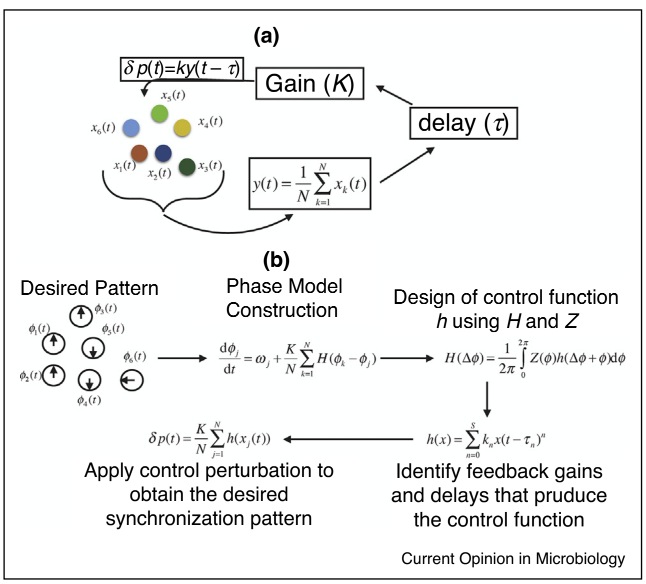
Many 'biological clocks' also exhibited an intriguing behavior: the oscillations are 'noisy', where the cycle-to-cycle period can fluctuate [4]. In the 1980s and 1990s, studies on chaos theory showed that in high-dimensional nonlinear dynamical systems, limit cycle oscillations can lose stability and, often through a sequence of bifurcations, a chaotic attractor can be obtained [5]. A tacit assumption emerged that irregular (or chaotic) behavior can be associated with a dynamical disease (e.g. heart arrhythmia), while low-dimensional, often periodic, behavior indicates a healthy state. Chaos control techniques were thus developed to suppress the chaotic behavior, most importantly, by stabilizing unstable periodic orbits embedded in the chaotic attractor [6]. While the techniques relied on standard engineering control methods, proportional or delayed feedback of a variable to a control parameter, the approaches opened way for applications of modern theories of nonlinear dynamics to control applications. These techniques were successfully implemented in the Belousov–Zhabotinsky (BZ) reaction [7], electrochemical [8], enzymatic [9], and gas-phase [10] systems. In distributed systems, for example, on the surface of a single crystal Pt catalyst, spatiotemporal turbulence can develop where chaos exists in both time and space. Nobel Laureate Gerhard Ertl described in his Nobel address that such spatiotemporal chaos can be regulated through series of regular spatial structures with use of a delayed feedback of surface coverages to the partial pressure of CO during CO oxidation [11]. Similar, delayed linear feedback techniques were shown to be effective in tuning dynamical structures in distributed (e.g. BZ reaction [12,13]) and discrete (e.g. electrochemical reactions on electrode arrays [14–16] and BZ catalyst beads [17]) systems.

Starting in the 1990s, it become clear that in many biological systems the complex behavior (that may include chaos) arises because of interactions between different oscillatory processes: A universal concept, synchronization, was developed to describe the adjustment of oscillations properties due to the interactions [18]. The interactions could occur among cells of relatively similar dynamics, for example, the circadian clock cells in the mammalian suprachiasmatic nuclei [19], or between very different cycles, for example, the synchronization of the cardiorespiratory system [20]. Throughout this review, we focus on a type of synchronization in which the phase differences of the units are bounded (e.g. phase locked) [18]. Analysis of many biological systems point to the fact that physiological operation of living systems requires an optimal level of synchronization: when the synchronization structure breaks down, a dynamical disease can develop, for example, hypersynchronous neural discharges in epileptic seizures or lack of synchrony in heart arrhythmias [21]. When the optimal synchronization structure is broken, an intervention, 'synchronization engineering' is required to re-establish the physiological condition. In this paper, we give an overview of synchronization engineering techniques, with emphasis on recent developments.

Synchronization engineering with global feedback

As a fundamental control technique, global feedback has been a valuable tool for inducing different synchronization structures. The schematic of the technique is shown in Figure 1a. Consider N discrete dynamical units, and assume that measurements can be made through an observable variable in each unit as a function of time,

Figure 1



Schematic for feedback design for synchronization of oscillatory processes in discrete units. **(a)** Linear delayed feedback. Mean value of experimental observables, x_j ($j = 1, 2, \ldots, N$, where N is the number of units) is fed back to a system parameter (p) with gain K and delay τ. **(b)** Phase model based synchronization engineering. (i) Desired pattern consists of target phase values (ϕ_j) of the units. (ii) Phase model is constructed that generates the same asymptotic pattern with global coupling strength K and phase interaction function H in the heterogeneous population of oscillators with natural frequency of ω_j. (iii) Design of control function h is generated with deconvolution using the phase response function Z and H. (iv) Gains and delays for polynomial delayed feedbacks are determined with nonlinear fitting to h. (v) The application of delayed polynomial feedback is expected to generate the desired phase pattern.

$x_j(t)$, $j = 1, 2, \ldots, N$. (Without loss of generality, it is assumed that the observable variable has zero mean.) During the control, a global variable is constructed from the individual measurements, $y(t) = f(x_1(t), x_2(t), \ldots, x_N(t))$, and a control perturbation, $\delta p(t)$, is applied to a system parameter, p, around a set value, p_0:

$$p(t) = p_0 + \delta p(t) \tag{1}$$

and

$$\delta p(t) = K(y(t-\tau)) \tag{2}$$

where K is a feedback gain and τ is the delay. Even in the simplest form of the control law, simply averaging the variables, complex synchronization structures can be induced in oscillatory systems [22,23].

The synchronization structures can be decoded with a phenomenological description of the oscillatory process using phase models [18]. For an oscillatory signal $x_j(t)$, the phase $\phi_j(t)$ indicates the angle of the oscillations along an appropriately defined two-dimensional state space (see Figure 2a). (Such reconstruction can often be obtained with the use of Hilbert transform approach [18].) For two oscillators, phase locking occurs when the phase difference remains constant. If this phase difference is around 0, π, or some other value, the state is in-phase, anti-phase, or out-of-phase synchronized, respectively (see Figure 2b). In large population of oscillators, phase clustering can occur (see Figure 2c). Groups of elements are formed, in each group the phase being the same but different from those of the other groups (e.g. one or two-cluster states). If the elements are distributed along the limit cycle, a desynchronized state can form.

When sufficiently strong coupling occurs between the oscillating units (e.g. due to mass transfer of substances from one unit to another, or through global constraints), synchronization patterns can occur in a system. For example, in electrochemical systems a variety of in-phase, anti-phase, and out-of-phase synchronized current oscillations were obtained with two electrodes [24,25], and one, two, three, and even higher number of clusters were observed with an electrode array [24]. Similar structures can occur with BZ reaction in CSTRs, microdroplets, and BZ beads [26,27].

Several studies have been performed to show that with the delayed global linear feedback new type of synchronization structures can be induced, or existing structures can be tuned [14,22,23]. As an important example, desynchronization of oscillators was achieved with properly chosen feedback gain and delay [22,23]. With strong feedback and large delays, birhythmicity (co-existence